STUDY OF METHODS OF IMPROVING THE PERFORMANCE OF THE LANGLEY RESEARCH CENTER TRANSONIC DYNAMICS TUNNEL (TDT)

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BY
SVERDRUP & PARCEL AND ASSOCIATES, Inc.
ST. LOUIS, MISSOURI

I

FOREWORD

This report is submitted in fulfillment of NASA Contract NAS1-11687 dated June 13, 1972 between National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, and Sverdrup & Parcel and Associates, Inc., St. Louis, Missouri.

SUMMARY

A study has been made to provide improved performance for the Transonic Dynamics Tunnel (TDT) at the Langley Research Center. The major effort was directed to obtaining increased dynamic pressure in the Mach number range from 0.8 to 1.2, but methods to increase Mach number capability were also considered.

Methods that were considered to improve tunnel performance included the following:

Increased Dynamic Pressure

A. Operate the tunnel at higher total pressure.

1. Increase tunnel drive system power.

2. Increase tunnel shell pressure capability.

B. Provide an auxiliary compressor system operating on the test section plenum.

C. Improve the performance of the tunnel circuit by reducing losses.

D. Greatly reduce the temperature of the test medium.

E. Reduce the size of the test section.

F. Substitute a better high molecular weight fluid for Freon-12.

Increased Mach Number

A. Provide nozzle block inserts.

B. Provide a variable geometry nozzle.

C. Change the test section wall configuration.

D. Provide an auxiliary compressor system for test section plenum ventilation.

The most economical approach for obtaining a large increase in dynamic pressure was found to be by increasing main drive power. A large increase can be obtained by rewinding the drive motor and making certain other accompanying modifications at relatively modest costs. However, to provide larger increases would require the installation of a new drive and tunnel compressor system as well as additional circuit cooling and tunnel pressurization. This latter method has the disadvantages, as compared to an auxiliary compressor system which was studied extensively, of requiring a rather long tunnel downtime to effect the modifications. None of the methods examined for increasing Mach number above Mach 1.2 appeared to offer much promise of success in the TDT.

It has been concluded that the TDT was well designed at the time it was built, considering the limitations that were undoubtedly imposed on space and cost. Advantage appears to have been taken of nearly all methods to gain maximum performance with minimum expenditure. Such conditions make methods for significant improvement in performance very costly.

TABLE OF CONTENTS

	Foreword	i
	Summary	ii
I	INTRODUCTION	1
II	EXISTING FACILITY PERFORMANCE	3
	A. Facility Description and Capability	3
	B. Circuit Pressure-Loss Investigation	4
	1. Circuit Performance Evaluation	4
	2. Circuit Pressure Losses	6
III	PERFORMANCE IMPROVEMENT METHODS	10
	A. Increase Drive Power	10
	B. Reduce Tunnel Temperature	11
	C. Reduce Test Section Size	11
	D. Change the Test Medium	12
	E. Install an Auxiliary Compressor System	12
	F. Increase the Mach Number Capability	14
	G. Reduce Circuit Losses	15
IV	POSSIBLE MODIFICATIONS	18
	A. Reduce Circuit Losses	18
	B. Increase Drive Power	19
	1. General	19
	2. Performance	22
	3. Costs and Tunnel Downtime	23
	C. Add Auxiliary Compressor System	26
	1. General	26
	2. Auxiliary Compressor System Layout	27

3. Auxiliary Compressor System Requirements 31
4. Auxiliary System Performance 33
5. Costs and Tunnel Downtime 34

V SECONDARY IMPACT OF POSSIBLE MODIFICATIONS 36

A. Tunnel Shell Pressurization 36

1. General 36
2. Recommendations 38

B. Tunnel Cooling 38

1. General 38
2. Cooling Methods 39
3. Cooling System Costs 40

C. Circuit Compressor 40

1. General 40
2. Increased Main Drive Power 41
3. Auxiliary Compressor System 42
4. Tunnel Pressurization 42

D. Gas Charging System 42

1. General 42
2. Freon System 43
3. Air System 43
4. Other Considerations 44

E. Electrical Power Supply 44

VI CONCLUSIONS 47

VII RECOMMENDATIONS 49

Appendix A - Tables 50
Appendix B - Figures 56
Appendix C - Circuit Pressure Losses 83
Appendix D - Proposed Test Program 129
Appendix E - Performance Improvement for Several Modification Methods 140
Appendix F - Auxiliary Compressor System 173
Appendix G - Circuit Pressurization 227
Appendix H - Modification Costs 257

I INTRODUCTION

The transonic dynamics tunnel (TDT) at Langley was designed to fill the need for transonic testing of dynamic models of large size in order to permit simulation of structural properties of aircraft or spacecraft. Aeroelastic testing in the facility includes the study of flutter, aerodynamic loads, and input response. The Langley TDT is a large, continuous-flow, variable density, single return tunnel powered by a 20,000 hp main drive compressor. The TDT was rebuilt into its present configuration during the 1955-1960 period from the original 19-foot Pressure Tunnel which had a pressure capability of 2.5 atmospheres. Tunnel performance is limited in the transonic range by the main drive power and at lower speeds by currently-imposed tunnel shell pressurization limits of 2500 psfa.

The tunnel operates using either air or Freon-12 (dichlorodifluoromethane) as a test medium. The tunnel is operated about 90% of the time with Freon-12 of about 95% purity. This provides a high molecular weight gas with a speed of sound about one-half that of air. Freon-12 has advantages in aeroelastic research of providing higher dynamic pressure and permitting closer simulation of Froude and Reynolds numbers for a given amount of drive power, of simplifying model construction by reducing the natural frequency and increasing the allowable weight for model scaling, and of simplifying data readout because of a slower time scale.

A progressively larger gap has been developing between the dynamic pressure and Reynolds numbers existing on aircraft during

flight and those available on models during wind tunnel tests. This gap results from the fact that each successive generation of aircraft is generally larger and faster than its predecessor, whereas very little progress is being made in providing larger or higher pressure tunnels. Extrapolating these effects has always been a major problem. The situation has been particularly disquieting at supercritical Mach numbers where trends to assist in the extrapolation cannot be established. Greater dynamic pressure and Reynolds number capability in this and similar wind tunnels would greatly alleviate the problem.

Because of its Freon-12 capability, it is very desirable to increase the performance of the Langley TDT. Accordingly, a study was initiated in June, 1972 to develop technical information and to make recommendations regarding modifications to the TDT. It is desired to obtain maximum improved performance within the constraints of minimum alteration to the tunnel basic shell and main compressor, and minimum tunnel downtime. The results of this study are presented herein.

II EXISTING FACILITY PERFORMANCE

A. FACILITY DESCRIPTION AND CAPABILITY

The Langley TDT is a continuous-flow tunnel which operates from Mach numbers of 0.1 to 1.2, at stagnation pressures from 30 to 2120 psfa, at stagnation temperatures from 70 to 130°F, and with either air or Freon-12 as a test medium. An extensive description of facility components, test equipment, and performance capability is illustrated in Langley Working Paper LWP-799 dated September 23, 1969. The basic limitation on dynamic pressure is imposed by available power. Additionally, the performance is limited by tunnel cooling capability, the fan and its drive structural capability, and at lower Mach numbers by the tunnel circuit pressure capability.

The TDT main drive is designed to deliver 20,000 hp in either of two speed-ranges as required for air and Freon-12 operation. The system is also capable of limited operation at 115% and 130% of rated load with air and Freon-12, respectively. For this study, the normal rated power performance was selected for comparative purposes. It was assumed that comparable increases in performance resulting from overload operation and/or drive power rating above the nominal quoted could be obtained with the recommended modes of modification. The maximum dynamic and total pressures which are available in the TDT at normal rated power are illustrated in Figure 1, Appendix B.

B. CIRCUIT PRESSURE-LOSS INVESTIGATION

1. Circuit Performance Evaluation

Wind tunnel ducting elements produce friction and momentum losses which impose the loads on the tunnel main drive and cooling system. Common measures of wind tunnel design are energy ratio and the power per unit area at a pressure of one atmosphere and a temperature of 60°F. The main drive shaft horsepower requirements for the Langley TDT and several other large-scale wind tunnels, all of which operate with air as a test medium, are illustrated in Figure 2. The TDT performance presented in Figure 2 was scaled from the performance presented in Figure 1.

The data in Figure 2 indicates the low power requirements for Freon-12 operation. In addition, the data indicates that with air as a test medium the TDT requires more horsepower than the other two NASA tunnels. It is suspected that the poor TDT performance results from higher tunnel losses and perhaps a lower fan efficiency. Considering that the TDT was rebuilt from the Langley 19-foot tunnel, it is reasonable to assume that compromises of the various ducting elements with associated higher losses could not be avoided. In the Mach number range from 0.8 to 1.2 which is the primary interest of this study, the high tunnel losses can probably be attributed to utilization of diffuser flap suction, first diffuser flow separation and high velocity at the first two corners. Because no loss measurements have ever been made for the TDT detailed investigation of circuit losses was included in this study.

A preliminary evaluation of circuit components was obtained by making pressure loss calculations assuming a test section Mach number of 0.70, a total pressure of 500 psfa, and air as the test medium.

Conventional techniques for computing wind tunnel ducting losses and preliminary information with regard to the TDT physical characteristics were utilized. The relevant assumptions, supporting equations and summaries of the engineering computations are presented in Appendix C. A tunnel layout which indicates the various ducting elements for which computations were made is presented in Figure 3. The section number is at the upstream end of the ducting element.

The results of these preliminary loss calculations are presented in Figure 4. The data in Figure 4 indicate that several ducting components may be considered as high loss elements. The highest loss was indicated to occur in the test section; however, the friction loss coefficient was somewhat arbitrarily assumed. Based on this preliminary work to determine the TDT circuit pressure losses, the following conclusions were made:

a. For most tunnel components, the analytical procedures provide a good indication of the element pressure loss. However, the losses for such elements as the test section, the diffuser flaps, and the first diffuser can best be determined by experimental means. Consequently, the conduct of a pressure loss test in the Langley TDT was recommended. A discussion of the test program is presented in Appendix D. The test was considered particularly important since it was believed prudent to base possible recommended circuit modifications upon experimental results.

b. To provide optimum performance, a subsonic diffuser should have an area ratio of at least 4.0. Although the installed angle (6.5^{o}) of the west leg diffuser is considered satisfactory, the diffuser area ratio is only 2.8, if one selects Station 80 as the diffuser entrance. This would indicate that the west leg diffuser is about 68 feet too short to provide a good pressure recovery.

c. For the assumed conditions, the calculated fan compression ratio of 1.075, which corresponds to a circuit pressure loss of 35.4 psfa, was lower than expected. This indicated that the TDT performance might also be inhibited by poor fan performance, i.e., low fan efficiency. For this reason, it is recommended that an attempt be made to measure the fan efficiency during the TDT pressure loss test.

2. Circuit Pressure Losses

Because of higher priority test programs for the Langley TDT, it became impossible to schedule the recommended pressure loss test within the contract period of this study. Without the experimental data, the need for additional circuit pressure loss calculations arose. These data were needed to indicate if any minor circuit component modifications would provide significant increases in tunnel performance. In addition, the data were needed to aid the evaluation of an auxiliary compressor system for plenum ventilation.

The loss-calculation procedures and the basic tunnel layout (see Figure 3) have been previously discussed. Several significant changes for these additional calculations were made. These include: (1) the breakup of the east leg annular diffuser into two loss elements by addition of Section 1a at Station E132, (2) the inclusion of

the safety screen which is installed at Corner B (see Appendix C), (3) the reduction of the assumed test section friction loss coefficient by a factor of two, (4) the assumption that for Mach numbers greater than 0.70, the west leg diffuser flow is separated, (5) the inclusion of a fictitious Section 9a to account for shock and flap losses (the associated engineering analysis and the resulting loss coefficients for various Mach numbers are presented in Appendix C), and (6) the utilization of updated information with regard to the tunnel physical characteristics (these data are presented in Table I).

The pressure loss calculations were made for both air and freon operation at Mach numbers of 0.4, 0.7, 0.9, 1.0, 1.1, and 1.2 assuming near maximum power test conditions. The initial conditions for the loss calculations are a function of the fan compression ratio and efficiency, and the backleg pressure losses. The initial conditions, which are presented in Appendix C, were determined utilizing the best available data and assumed values as required.

An assessment of the pressure loss calculations can be obtained by comparison of calculated and known fan compression ratios. The fan compression ratio is, of course, that corresponding to the total circuit pressure loss. Although documentation of the TDT fan compression ratio was not available, some unpublished data provided by NASA during October 1972 were utilized to obtain an indication of the TDT fan compression ratio with air as a test medium. Considering that the higher density of freon results in lower friction losses, the TDT fan compression ratios for operation with freon were estimated to

be 80 percent of those for air. These data are considered to be the best indication of the TDT fan compression ratios. A comparison of these data with the results of the pressure loss calculations is presented in Figure 5. The data in Figure 5 indicates that the pressure loss calculations produce reasonable results.

A summary of the pressure loss calculations is presented in Tables 2 and 3. A discussion of the data presented as well as the distribution of total pressure and Mach number around the circuit is included in Appendix C.

The pressure loss of each circuit element in percent of total pressure loss is presented in Figures 6 and 7 for Mach numbers 0.4 and 1.0, respectively. These data indicate that only eight circuit elements should be considered for possible modification. The percent loss of these various elements, as a function of Mach number is presented in Figures 8 to 11. The data in Figures 8 to 11 indicate that for the Mach number range from 0.8 to 1.2 the components which exhibit the most potential for possible modification are the flaps, the east leg diffuser and the two screens. The possible modifications and the margins of improvement will be discussed in another section.

Based upon the results of the TDT pressure loss calculations, the following conclusions are made:

a. The pressure loss calculations provide a good indication of the loss for the various circuit elements. However, because of the numerous assumptions made for this study, particularly concerning the test leg pressure losses, experimental data should be obtained prior to initiating any modifications indicated by this study.

b. Only four of the circuit elements; the flaps, the first diffuser and the two screens, appear to be good candidates for possible modification. The largest increase in TDT performance could be obtained by replacement of the flap operation with an auxiliary suction system for plenum ventilation.

III PERFORMANCE IMPROVEMENT METHODS

Several alternative modification methods for improving the TDT performance were considered during the conduct of this study. The various methods are briefly described as follows:

A. INCREASE DRIVE POWER

Since the dyanmic pressure increases directly with increases in drive power, this modification technique would appear to be the most straight-forward method possible. Several methods were explored to obtain increased power in the main drive system. These included (1) additional cooling of the existing motor to permit greater output, (2) rewinding of the existing motor for greater output, and (3) new high power output drive systems.

It was deemed essential that the present two speed-ranges be retained in order to be compatible with speeds required for the compressor blading in the two test mediums, freon and air. This criterion, among other factors, restricted consideration of rewinding and a new motor to 30,000 and 50,000 hp systems, respectively. The performance gains and the costs associated with these two alternatives are discussed in Section IV.

It was S&P's initial thought that a significant power increase might be possible by providing additional cooling for the existing motor. Such cooling might take the form of refrigerated air, larger quantities of air, or other gas cooling mediums. However, the drive system manufacturer believed that little or no increase in power would be possible with this approach.

B. REDUCE TUNNEL TEMPERATURE

The dynamic pressure available for a given horsepower varies inversely with the square root of the tunnel stagnation temperature. Consequently, large decreases in temperature are required to obtain significant increases in performance. Refrigeration does not involve an increase in the stresses in the model nor a departure from the conditions of dynamic similarity. In addition to high cost, some practical difficulties which make this alternative prohibitive for the TDT are:

1. When operating with Freon-12 as the test medium, condensation would occur at relatively modest temperature reductions due to the physical properties of the gas.

2. Severe metallurgical problems would arise with the tunnel structure at low temperatures unless internal insulation and/or shell heating were provided.

3. TDT aeroelastic test model materials and their behavior at low temperature were considered to present an insurmountable problem. Model heating was not considered to be feasible.

C. REDUCE TEST SECTION SIZE

The power required to operate a wind tunnel is directly proportional to the test section cross sectional area. Therefore, for a given installed power, the dynamic pressure is increased as the area of the test section is decreased. Reasons that such a modification for the TDT was not deemed feasible are:

1. Smaller test models would be required, which would negate any improvement in Reynolds number capability.

2. Fan pressure ratio requirement would be increased, which would necessitate a fan of different design, possibly multi-stage.

3. Formidable problems with redesign and reconstruction of a smaller test section would be expected. Therefore, the performance improvement gain would not be expected to be economically feasible.

D. CHANGE THE TEST MEDIUM

As indicated by the freon operation, the TDT dynamic pressure performance increases with an increase in the molecular weight of the test medium. Sulfur hexafluoride, SF_6, has a higher molecular weight than Freon-12, but was more toxic and expensive. When the 19-ft tunnel was modified, SF_6 and nine other gases were investigated. It was concluded that the reasoning for selecting Freon-12 for the test medium was still valid, and, consequently, the consideration of other gases was dismissed.

E. INSTALL AN AUXILIARY COMPRESSOR SYSTEM

To alleviate choking in a transonic wind tunnel, a portion of the test section flow must be bypassed. This is accomplished by applying suction to the test section plenum. Plenum flow removal may be accomplished by utilization of diffuser flap suction, as is presently the case for the TDT, or by utilization of an auxiliary compressor system. Because of the very high losses normally associated with diffuser flap suction, an auxiliary compressor system appeared to offer very significant performance improvement for the TDT. The auxiliary compressor system performance, layout, and costs

are discussed in Section IV. Some of the advantages that this system offers over other methods include the following:

1. Minimum tunnel down-time would be incurred because design, procurement, and installation of nearly all of the system could be accomplished while the TDT remained in operation. The system would be virtually independent of the tunnel except for inlet and outlet connections.

2. This alternative would allow retention of the existing circuit compressor, drive system, and cooler. Since no additional power is required in the main circuit drive system, and auxiliary cooling can be provided in external coolers for the auxiliary compressor system, no modification of the main system is required. An exception, of course, would be if the decision were made to both increase the main drive power and add auxiliary suction.

3. Utilization of auxiliary suction not only eliminates the plenum pumping load on the main drive, but it can provide a gain in first diffuser performance if the flow is properly returned to the tunnel. In some cases, resulting improvement in dynamic pressure can be greater than that obtained by adding equal power to the main drive.

4. The auxiliary suction system could easily be designed to provide the necessary plenum flow removal at supersonic Mach numbers. Consequently, the auxiliary compressor system could aid in increasing the Mach number performance of the TDT.

5. Since the auxiliary compressor plant is essentially an independent system, several "spin-off" advantages would occur. For example, the system could be utilized for TDT pressure control, or to support the operation of other wind tunnels.

F. INCREASE THE MACH NUMBER CAPABILITY

Investigation of the feasibility of increasing the TDT Mach number capability produced the following observations:

1. Although an auxiliary compressor system could be designed to provide the necessary plenum flow removal at Mach 1.4, an increase in the Freon system compression ratio from 2.42 to about 3.0 would be required. In addition, an increase in the main fan pressure ratio capability possibly would also be required. This would be dependent on the magnitude in the reduction of circuit losses. However, it is expected that the fan pressure ratio requirements at Mach 1.4 would exceed the present fan design ratio of 1.20 in Freon. This would indicate that modifications to include a two stage fan would also be necessary.

2. The present TDT usable test section length, that is, the length for which uniform flow is developed at M = 1.2, is only about 10 ft. This usable length will decrease if higher Mach numbers are attempted to be generated with a sonic nozzle and plenum suction. In addition, the plenum flow removal requirements increase rapidly with increase in Mach number in wind tunnels which utilize sonic nozzles. Consequently, a supersonic nozzle would be required to

obtain a Mach number of 1.4. Because of the high cost and long downtime associated with a flexible nozzle, the feasibility of installing nozzle inserts to obtain specific Mach numbers was considered. Because of the large size of the TDT test section and because complete flutter models require continuous Mach number coverage, nozzle inserts were not considered desirable.

3. Because of the inherent characteristics of slotted test section walls, the test section Mach number distribution might be unacceptable at higher Mach numbers. This possibility indicates the need for a slot development program. The technology, however, indicates that either a perforated wall or a slotted wall with perforated inserts is superior to a slotted wall at Mach 1.4. Consequently, increasing the TDT Mach number capability would probably require a new test section configuration.

It was concluded that the necessary modifications to obtain higher Mach number capability for the TDT was in violation of the study constraints of minimum downtime and cost. For this reason, extending the TDT Mach number capability was eliminated from further consideration.

G. REDUCE CIRCUIT LOSSES

The results of the circuit loss calculations indicated that only a few of the circuit components exhibited potential for possible modification to improve the TDT performance. These elements include the flaps, the east and west leg diffusers, and the screens downstream of the fan and at Corner B. A discussion of possible improvements, the analyses for which are presented in Appendix E, follows.

Brief study of the screen at Corner B revealed that increasing the porosity of the fine mesh screen from about 77 to 88 percent would increase the TDT performance at M = 1.0 by 2.8 percent. The cost of such a modification would be negligible. Because of a slight decrease in fan safety, however, this modification is not recommended.

Three possibilities were considered for modification of the east leg diffuser and screen. These included (1) moving the screen nearer the entrance of the annular diffuser, (2) replacing the screen with one which had a significantly lower pressure loss coefficient, and (3) replacing the screen with vortex generators on the nacelle and perhaps the tunnel shell. The results of the analysis indicated that moving the screen would not provide lower losses, and that a reduction of the screen loss coefficient by 37.5 percent would only provide for a 4.2 percent increase in performance. For the latter method, it was estimated that up to an 8 percent increase in performance could be available at M = 1.0. Because of the numerous assumptions which were involved and considering the nature of the modification, an experimental program to evaluate this proposed modification is required. It is recommended that such a development program be conducted at the TDT. The cost of the modification and the supporting tests will be minimal.

Two possibilities were considered for possible modification to the west leg transition and diffuser. The first, which involved extending a splitter plate to Station 214, did not provide any performance increase. The second approach involved installation of

vortex generators near the entrance of the diffuser. As previously pointed out, the TDT west leg diffuser is too short, hence the efficiency could perhaps be improved. Furthermore, vortex generators could possibly inhibit flow separation which has been assumed to occur at Mach numbers above 0.7. If separation could be prevented, an increase in performance up to 7.7% could be realized. Because the cost of such a modification is negligible, it is recommended that vortex generators of common design be installed at about Station 109. The effect of such modification on the TDT performance could easily be evaluated.

The results of the circuit loss calculations indicate that the highest tunnel losses are associated with flap operation. The data in Figure 10 indicate that these losses vary from about 4$ at M = 0.8 to about 58% at M = 1.2. It is believed that a very large increase in TDT performance can be obtained by replacement of flap suction with an auxiliary compressor system for plenum ventilation. The performance improvement and the costs associated with this modification are discussed in Section IV. Should an auxiliary suction system prove economically not feasible, it is believed that some small performance improvement could be obtained by optimizing the TDT flap settings for various Mach numbers. Current practice in the TDT is to set four flap settings for four ranges of Mach numbers. Possible performance improvement is subject to verification by tests at the TDT.

IV POSSIBLE MODIFICATIONS

A. REDUCE CIRCUIT LOSSES

Investigation of several possible modifications to the tunnel circuit indicates that no single modification would lead to a significant increase in performance. Possible improvement cannot be easily predicted, but could be experimentally determined. Because minimal costs are involved, the circuit modifications are considered likely candidates for recommended modifications. It is pointed out that although no single modification is significant, the cleanup of the entire circuit could be. For example, for the previously discussed modifications to the Corner B screen and the east and west leg diffusers, a 16.0% gain in performance may be available at M = 1.0.

For the possible modifications (based on the analyses presented in Appendix E) the estimated performance which may be available in the TDT for a complete circuit cleanup is presented in Figure 12. These data indicate that for both air and freon an increase in performance from about 8.5% at M = 1.2 to about 20% at M = 0.8 may be available with a complete circuit cleanup. In addition, the potential performance improvement is within the present pressure operating limits.

A formal cost estimate for the possible modifications was not made. It is believed that a complete circuit cleanup could be accomplished for less than $50,000. In addition, tunnel down-time

would be insignificant, since it is believed that the modifications could be scheduled during normal tunnel down-time periods. It is assumed that the test time for experimental verification of the improvement in performance can be made available.

B. INCREASE DRIVE POWER

Of the several methods which were explored to obtain increased power in the main drive system, two were selected for estimation of performance gains and modification costs. These include (1) rewinding of the existing motor for 30,000 hp output, and (2) installation of a new 50,000 hp drive system. It was deemed essential that the present two speed-ranges be retained in order to be compatible with speeds required for the compressor blading in the two test mediums, freon and air. These two possible modification alternatives are discussed below. A detailed discussion of the impact of the possible modifications upon various tunnel components is presented in Section V. The engineering work which supports the estimates of performance improvement is presented in Appendix E.

1. General

a. Rewind Existing Motor

The manufacturer has indicated that the existing motor can be rewound for a 30,000 hp rating and the same two-speed operation as is presently available. Presumably, the motor would be capable of some overload and possibly some capability above the nominal 30,000 hp which could then be utilized to obtain about a 50% increase in power output.

There appears to be no reason why the rewinding could not be accomplished in the nacelle, at somewhat greater cost than in the shop. However, the savings realized from not having to cut the shell and the nacelle, remove the motor and transport it to and from the manufacturer, reinstall the motor and then reweld the shell, would far more than offset the extra cost of rewinding inside the nacelle. Very appreciable savings in tunnel shut-down time would also be realized by rewinding inside the tunnel. This rewinding of both the stator and the rotor inside the nacelle is possible because the original design of this motor provided for stator shift (as indicated on Westinghouse Electric Corp. Drawing 75-J-89). This permits the stator to be shifted enough horizontally to expose both the rotor and the stator windings without disturbing the rotor and the rotor bearings, permitting replacement of the existing rotor and stator windings with new windings.

Modifications which would be necessary to accompany this repowering would consist of modifications to strengthen the circuit compressor, a new liquid rheostat and speed control equipment, additional circuit cooling capacity, and additional cooling capacity for the main drive motor, liquid rheostat and eddy current brake.

b. New Drive System

A large increase in dynamic pressure capability for the TDT can be obtained by installing an entirely new higher power drive system. It appears that two-speed drive systems up to 50,000 hp could be installed in the existing nacelle. By increasing the voltage of the motor to 13,800 volts (15 kV class), its size and weight could be

held down to a point where it could probably be designed to fit inside the present nacelle, and perhaps even to fit the existing sole plate. New drive system components required for this amount of power increase would include the fan and fan bearings (both radial and thrust), the motor and bearings, couplings, eddy current brake, liquid rheostat, speed control equipment, and possibly new stator blading for the added loads. Additional cooling for the motor and liquid rheostat, greatly increased tunnel circuit cooling capacity, and possible shell strengthening of some components would also be required.

This modification would also require extensive cutting of the existing tunnel nacelle, and shoring and extensive cutting of the pressure shell; and would require rigging to remove the existing motor drive system and to install the new drive system. It appears that the foundation and drive supports, up to and perhaps including the sole plate, would be satisfactory for a new drive of this capacity. It is anticipated that a large opening could be cut into the north side of the northeast corner of the tunnel circuit, after shoring the tunnel shell, to remove the existing drive and to install the new drive. Considering the size of the east leg of the tunnel and the proximity of the adjacent buildings, it does not appear feasible to replace the drive through an opening in the top of the shell above the drive foundation. Neither is it possible to go through the bottom of the shell because of the foundation; and there is not enough room between the north face of the drive foundation

and the northeast corner girder to cut a large enough opening in the bottom of the tunnel leg to work in that vicinity.

2. Performance

The input power requirements for a closed circuit wind tunnel are a function of the fan exit pressure, compression ratio, volume flow and efficiency, as well as the test medium. For a specific Mach number and corresponding pressure ratio, and assuming that the fan efficiency remains constant, the fan exit pressure is directly proportional to fan power. The tunnel dynamic pressure, therefore, increases directly with increase in fan power.

The estimated performance for the TDT for the proposed 30,000 hp rewind option and the 50,000 hp new motor option is shown in Figures 13 and 14 for air and freon respectively. The data, which are presented only for the Mach number range of primary interest, are compared with the present TDT performance.

The data in Figure 13 indicates that for both modification alternatives the improved performance with air is well within the present pressure operating limits for the TDT in the Mach number range from 0.8 to 1.2. The data in Figure 14 indicates that for the 30,000 hp option the improved performance with freon is within the present pressure operating limits in the Mach number range from 0.8 to 1.2. Procurement of new manometers, at a cost of about $20,000, and operation at pressures in excess of the present structural limits would be required for full utilization of 30,000 hp below M = 0.7.

The data in Figure 14 also indicate that for the 50,000 hp option, new manometers would be required to fully utilize the 50,000 hp at Mach number of 0.8 and above, and that operating pressures of about 138% of the present shell structural limit would be required for Mach numbers between 0.85 and 0.80 to fully utilize the 50,000 hp. The results of the study of the shell structure, which are discussed in Section V, indicated that little, if any, strengthening of the tunnel shell would be required for operation at 125% of the present shell structural limit. Because a significant increase in performance would be obtained over the full Mach range (a factor of at least two between Mach numbers 1.2 and 0.73), and because little or no cost would be incurred for shell strengthening, it is recommended that the tunnel pressure be limited to 125% of the presently defined tunnel structural limit of 2500 psf.

3. Costs and Tunnel Down-Time

a. 30,000 hp Rewound Drive Motor

The cost of this option is estimated as $2,800,000, which is based on motor rewinding, additional circuit cooling, additional drive motor and liquid rheostat cooling, new fan blades and fan blade sockets, new liquid rheostat, power supply increase, and tunnel circuit electrical and control equipment additions and modifications. Although costs have been estimated and included for new fan blades and fan blade sockets, there is a high probability that the existing fan blades and sockets will be suitable for this increase in the main power. Their suitability for the increased load will have to be resolved during preliminary or

final design if this option is chosen for further investigation. Cost back-up data for this estimate will be found in Appendix H.

The tunnel shut-down time for this option could be limited to two or three months by accumulating all of the new components at the site, and installing the new cooling tower and its pumping system prior to scheduled shut-down of the TDT for modification. Most of the items that require modification or replacement can be worked on simultaneously, and there would be no major work required on the tunnel circuit ducting, such as cutting large openings or reinforcing elements of the tunnel shell.

b. 50,000 hp New Drive Motor

The cost of this option is estimated as $11,500,000. This is based on a new 50,000 hp motor and drive; additional circuit cooling; additional motor and drive cooling; entire new fan, including hub, shaft, and bearings; power supply increase; tunnel circuit electrical and control equipment additions and modifications; additional freon storage capacity; and strengthening of miscellaneous tunnel shell components. Although costs have been estimated and included for all of the above items, it is probable that little or no shell strengthening will be required if the pressure increase is limited to 125% of the present structural limit of 2500 psfa; and it may be possible to salvage some of the fan components if a new thrust bearing can be designed to fit the existing shaft and to be suitable for the increased load. Even the fan blades and

sockets may prove to be satisfactory since the speed of the fan, which represents a major part of the design load on these items, is not being increased. If this option is selected for further investigation, a detailed analysis of the above items will be required during preliminary or final design to determine whether or not they will have to be replaced. Cost back-up data for this estimate will be found in Appendix H.

The tunnel shut-down time for this option could be limited to about six months by accumulating all of the new components at the site prior to scheduled shut-down. Many of the items that require modification or replacement can be worked on simultaneously. The refitting and rewelding of the large opening in the shell, for removing the old fan and drive and installing the new, can commence after the new fan and drive have been brought into the tunnel, and can proceed while they are being aligned and installed.

C. ADD AUXILIARY COMPRESSOR SYSTEM

The need for plenum flow removal in a transonic wind tunnel and the advantages of using an auxiliary compressor system for its accomplishment have been discussed in Section III. Two possible modification alternatives were selected for estimation of performance gains and modification costs. These include (1) installation of a 10,000 hp auxiliary compressor system with the present 20,000 hp main drive and (2) installation of a 15,000 hp auxiliary compressor system in conjunction with rewinding the main drive motor for 30,000 hp. The engineering work which supports the estimates of performance gains is presented in Appendix E. The engineering work associated with the auxiliary system compressor requirements is presented in Appendix F. A detailed discussion of the possible modification alternatives follows.

1. General

It was the intent of this study to investigate an auxiliary system capable of operation with both air and freon as a test medium, the primary motivation being that the same system inlet and exit ducting design would suffice for both air and freon. The results of the study indicated that for operation with air as compared to Freon-12, the compressor pressure ratio requirements are increased about 20 percent, and the compressor system volumetric capacity requirements are increased about 146% at the selected design Mach number of 1.2. It was decided, for the purposes of this study, to examine the performance of the auxiliary system for a freon-only

operation. In the planning and design concept, however, provisions have been made for modification for both air and freon operation.

Because the plenum flow removal requirements are only a function of test section Mach number and model blockage, the auxiliary system compressor pressure ratio and volume flow requirements are the same for both of the possible modification alternatives. In addition, the same system layout, i.e., ducting design, is satisfactory for both the 10,000 and 15,000 hp systems. The major differences between the two systems are in increased motor power and aftercooler capacity for the 15,000 hp auxiliary system.

The major advantage of the auxiliary system as compared to other possible TDT modifications appeared to be that the design, procurement, and installation of nearly all system components could be accomplished while the TDT remains in operation. Only a very short tunnel downtime was anticipated to allow the system tie-in to the main circuit ducting.

2. Auxiliary Compressor System Layout

The proposed layout for this system is shown on Figures 15 and 15a. Siting consideration of the auxiliary system inside the TDT loop by utilizing space north of the Electrical Equipment Building at ground level, above the Electrical Equipment Building by relocating the present cooling tower, and above the Freon Equipment Building, indicated that these spaces were either inadequate or the resultant building costs were excessively high. The location shown on Figure 15, now occupied by a parking lot immediately south of the TDT, appears to be the only possible location for a system of the required size.

The proposed auxiliary system layout illustrates both a two-compressor system (the two internal compressors) for freon-only operation, and the required modifications to provide a four-compressor system for air and freon operation. Although the available space south of the TDT is critical, it appears that a four-compressor system would fit within the available space. The two-compressor system for freon-only operation would easily fit into the required space.

The sizing of the system ducting was based on detailed ducting loss calculations using the same procedures as were used for the TDT circuit pressure-loss study. The physical characteristics of the auxiliary system ducting are presented in Table 4. It should be noted that although the selected ducting sizes provide reasonable pressure losses, should the auxiliary system modification alternative be selected, a cost trade-off study would be warranted during final system design.

The ducting loss calculations were made for both air and freon for test section Mach numbers of 0.8, 0.9, 1.0, 1.1, and 1.2. The auxiliary system would not be utilized at Mach numbers below 0.8. The pressure loss of each ducting element is presented in Figures 16 and 17 for the design conditions at Mach number 1.2. These data indicate that, except for three components for which high losses are unavoidable, the losses are fairly evenly distributed. The pressure recoveries of the auxiliary system ducting with freon as a test medium are presented in Figures 18 and 19.

Every possible location for the auxiliary system entrance cone at the test section plenum was investigated, and the one shown

was considered as the only suitable location. It was considered essential to have a 45° entrance cone to the 10' entrance duct. This entrance cone must be placed inside the plenum to avoid having to cut one of the four main ring girders on the test section pressure shell, and will have to be modified on its north side to clear the elevator. In addition, it will also require a modification to be made to the freon intake and exhaust manifold in the vicinity of this cone. The 10' duct must be placed in a concrete-lined pit beneath the west leg of the TDT, and located to avoid the existing foundations for the SW corner girder and the present freon storage tank. A tied expansion joint on the south end of the 10' duct will relieve the test section plenum of excessive anchor loads from the gas pressures inside this duct.

Construction of the concrete-lined trench for the 10' duct will present special problems because the groundwater level is very close to the ground surface. This will require dewatering, either with a well point system or trenching, during excavation for, and construction of the concrete trench, which must be heavy enough so that it won't float when the dewatering is discontinued. The 10' duct can be lowered into the south end of the trench in about 30' lengths and then shifted northward. This will require several circumferential welds to be made while the duct is in the concrete trench. The 45° inlet cone and the spoolpiece between it and the 10' elbow will be brought in pieces and field-fabricated after the opening has been cut in the test section pressure shell.

All compressors will have a 7'-6" inlet duct with appropriate connections to the 10' supply header and a safety screen, a 5'-6" outlet duct with a cooler, a 4'-0" bypass line for start-up and flow control, and the necessary isolation valves and expansion joints. The auxiliary system will exhaust through a 7'-6" line into a re-entry plenum immediately downstream of the test section. The flow will be injected back into the tunnel circuit parallel to the circuit gas flow through twelve inlet or re-entry flaps. The inlet plenum for flow re-entry to the circuit will be fabricated in several sections to be field-trimmed at assembly on the first diffuser.

Ideally, the re-entry flap exit Mach number should be somewhat higher than the free stream Mach number at the re-entry station, so that an ejector action is obtained. The re-entry station has been selected as Station 129. Because of the large size of the main circuit ducting and the fact that the area is increasing, and considering the small amount of re-entry flow, a significant ejector action is not expected. In addition, because of the high cost of a variable area flap system, it is recommended, at least for the purposes of this study, that a fixed flap area be utilized. Accordingly, the system was designed with twelve re-entry flaps, each with an area of 1.35 ft^2. At the design test conditions of Mach = 1.2, this system will produce a flap exit Mach number of 0.6. Somewhat lower Mach numbers are obtained at off-design conditions, but this was not considered detrimental to the system performance.

The new compressor building will be on pile foundations and will have a bridge crane for initial installation and later service of the compressors and their drive motors. The compressor foundations will be on separate pile-supported foundations. Although it would be possible to build a two-compressor system for freon operation initially, and later to add two more compressors for freon and air operation, this approach would increase the ultimate cost of the system. The decision to build a four-compressor system initially would minimize the ultimate cost of the total system.

3. Auxiliary Compressor System Requirements

The auxiliary compressor system requirements are defined by the compression ratio, the volume flow capacity, and the system power. The compressor pressure ratio requirements depend upon the main circuit losses between the test section and the flow re-entry station, the losses across the re-entry flaps, and the losses in the auxiliary system ducting. Based on the results of this study, the compressor operating pressure ratio requirements are shown in Figure 20. Assuming a 20% stall margin, the auxiliary system must be designed to deliver a pressure ratio of 2.42 with freon as a test medium.

The auxiliary system inlet volume flow requirements for various test section Mach numbers and plenum flow capacities are presented in Figure 21. For the minimum flow removal requirements and correcting for inlet ducting losses, the volume flow requirements are 3018, 3834, 4769, 6101, and 8709 cfs at M = 0.8, 0.9, 1.0, 1.1, and 1.2, respectively. For a 20% capacity margin, two 5,200 cfs compressors would be required for the Freon-12 system. The cost estimate

for this study assumes that the auxiliary compressors will be driven by synchronous motors. Bypass lines were provided to match the test section requirements.

The auxiliary system horsepower requirements are a function of the compressor pressure ratio, volume flow and efficiency, the test medium, and the compressor inlet pressure. For an arbitrarily assumed compressor efficiency, and for the pressure ratio and volume flow requirements indicated by this study, the compressor power per psf of inlet pressure is presented in Figure 22 for freon. Both a one and a two compressor configuration are shown. The data in Figure 22 indicate that only one compressor would have to be utilized for Mach numbers below 1.05. The compressor inlet pressure, Pci, is dependent upon the magnitude of tunnel performance improvement provided by the auxiliary system. A discussion of the estimated performance improvement is presented in another section of this report. The results of this work indicate that performance improvements from about 10% at Mach = 0.8 to about 64% at M = 1.2 would be provided by the auxiliary system. These margins of improvement would be available for both the 10,000 and 15,000 hp alternatives. For the 30,000 hp main drive rewind option, the auxiliary system inlet pressure increases by a factor of 1.5. So then, for the indicated margins of improvement and considering the inlet ducting losses, the compressor inlet pressures presented in Figure 23 were estimated. The auxiliary system power requirements are, therefore, defined as shown in Figure 24. The data in Figure 24 indicate that with the 20,000 hp drive,

each compressor should be powered for about 5,200 hp for a total of 10,400 hp. With the 30,000 hp rewind option, the data indicate that each compressor should be powered for about 7,800 hp for a total of about 15,600 hp. These systems will be referred to as the 10,000 and 15,000 hp auxiliary systems.

4. Auxiliary System Performance

Because of the high cost of matching the auxiliary system for operation with both air and freon, it was recommended that the initial system be designed for a freon-only operation. Consequently, the estimations of performance gains are limited to those for freon-only operation. The performance of the auxiliary system with air is suggested to be the subject of a detailed study during the final design phase of the auxiliary system.

The results of the circuit-loss calculations indicated that significant losses were associated with flap operation, which could be avoided by utilization of an auxiliary compressor system. The circuit losses associated with the high Mach numbers required to pump the plenum flow and with the re-entry of the flow into the diffuser have been presented in Figures 10 and 11. It is assumed that the re-entry losses can be eliminated, and the shock losses significantly reduced with utilization of an auxiliary system. Additional losses in the diffuser and transition were attributed to flow separation caused by the re-entry of the low energy plenum flow into the diffuser entrance.

A reduction of the circuit losses results in a decrease in the circuit pressure ratio requirements, and a corresponding increase in dynamic pressure performance. The detailed work associated with estimating the margins of improvement available with the auxiliary system is presented in Appendix E. The results of this work indicate that margins of improvement of 10.3, 23.2, 48.6, 57.0, and 64.0 percent at M = 0.8, 0.9, 1.0, 1.1, and 1.2, respectively, are available with an auxiliary system. These margins of improvement are applicable for utilization of an auxiliary system with both the 20,000 hp main drive and the proposed 30,000 hp main drive. The estimated performance of the TDT with utilization of an auxiliary system with the two drive powers is shown in Figure 25. The data in Figure 25 for the 10,000 hp auxiliary system indicates that the addition of an auxiliary system is more efficient at $M > 1.0$, but less efficient at $M < 1.0$, than adding an equal amount of power to the main drive.

5. Costs and Tunnel Downtime

a. 10,000 hp Auxiliary Compressor System

The cost of a 10,000 hp two-compressor auxiliary system suitable for freon-only operation is estimated as $6,000,000. The cost for a 10,000 hp four-compressor auxiliary system suitable for freon and air operation is estimated as $9,600,000. These are installed costs including the compressors, coolers and cooling tower, ducting, compressor building, and all associated equipment to complete the system described in paragraph 2 above. Cost back-up data for this estimate will be found in Appendix H.

The tunnel shut-down time for this option could be limited to three or four months with careful scheduling, and by constructing the compressor building and all of the ducting except that attached to the tunnel circuit shell, by installing the compressors and all associated equipment, and by accumulating all equipment and materials at the site prior to scheduled tunnel shut-down.

b. 15,000 hp Auxiliary Compressor System Coupled with Main Drive Rewind to 30,000 hp

The cost of a 15,000 hp two-compressor auxiliary system plus a rewind of the main drive motor to 30,000 hp suitable for freon-only operation is estimated as $9,100,000. The cost for a 15,000 hp four-compressor auxiliary system plus a 30,000 hp main drive motor rewind suitable for freon and air operation is estimated as $12,800,000. These are installed costs as listed in paragraph a. above and in paragraph B.3.a. above.

The tunnel shut-down time for this option could also be limited to three or four months with careful scheduling.

V SECONDARY IMPACT OF POSSIBLE MODIFICATIONS

A. TUNNEL SHELL PRESSURIZATION

1. General

In order to take advantage at the lower Mach numbers of the increased dynamic pressure that would become available with the improvement methods considered, it would be necessary in some cases to increase the total pressure of the test medium, either Freon-12 or air, above the present structural limit of 2,500 psfa in the stagnation chamber immediately upstream of the nozzle inlet. Consideration was given to increasing this pressure in increments up to a maximum as high as four times this value, or 10,000 psfa. A general review of the effect of these incremental increases was made on various tunnel components to determine to what extent they would be affected structurally. The study is of a general nature and will be found in Appendix G. In general, the conclusions reached were that:

a. For freon total operating pressure increases in the stagnation chamber up to 3,125 psfa (125% of the presently-defined tunnel structural limit of 2,500 psfa), little if any shell or component reinforcement would be required.

b. For freon operating pressure increases up to 3,750 psfa (150% of the presently-defined structural limit), some shell and component reinforcement would probably be required. Although the shutdown time would not be prohibitive, the cost of this reinforcement could not be justified for any of the improvement methods considered, except perhaps for an increase in main drive power up to about

50,000 hp. Even for this option, any added cost and the additional hazards incurred, when operating at 3,750 psfa instead of 3,125 psfa, would be difficult to justify; because the 50,000 hp can be fully utilized down to Mach number 0.85 if the pressure is limited to 3,125 psfa; and there is a significant improvement in the performance for Mach numbers below 0.85 also with pressure limited to 3,125 psfa.

c. For freon operating pressure increases up to 5,000 psfa (200% of the presently-defined structural limit), some shell and component reinforcement would certainly be required, and the stress reversals in some critical areas may prove to be unacceptable. The cost of this reinforcement could not be justified for any of the improvement methods considered, because the resulting increase in tunnel performance over that for an increase in operating pressure to 125% is in the low Mach number range (below the 0.8 to 1.2 range where improvement is needed).

d. A study of Figure 14 and of Table 5 indicates that it is difficult to justify a freon operating pressure up to 150% of the present limiting pressure even for a main power increase up to 50,000 hp; because if you follow the 125% structural limit curve from the point of its intersection with the 50,000 hp normal current load curve at Mach No. 0.85, you note that there is still a very appreciable performance increase at Mach numbers below 0.85. For a 10,000 hp auxiliary compressor system mated with the present 20,000 hp main drive, or for a rewound main drive motor up to 30,000 hp,

the present tunnel operating pressures are sufficient for the Mach 0.8 to 1.2 range where improvement is needed. If a 15,000 hp auxiliary system is mated with a 30,000 hp rewould main drive motor, the pressures would have to be increased to about 125% of present pressure levels to make full use of the available dynamic pressure down to a Mach number of 0.8.

2. Recommendations

No increase in tunnel limiting pressure is recommended for any of the possible modifications considered, except for the 50,000 hp main drive option or the 30,000 hp main drive with the 15,000 hp auxiliary compressor system option. For these two options, a pressure increase to 125% of the presently-defined limit should be considered. Before operating pressures are increased, however, a detailed structural analysis of all critical areas and details should be made to determine how much the operating pressures can be increased with little or no added reinforcement. The study included in Appendix G will serve as a general guide to help pinpoint those areas that require detailed consideration. After any necessary reinforcement has been made, it is recommended that a pneumatic pressure proof test be made up to 150% of the anticipated new operating pressures.

B. TUNNEL COOLING

1. General

Additional tunnel circuit cooling is required for any performance improvement method which adds power to the main drive

system. The auxiliary compressor system, which has coolers in that circuit, would not impose any added cooling load on the main circuit cooling system.

2. Cooling Methods

Two methods to provide additional cooling in the tunnel circuit were considered. These were (1) the addition of cooler surface area in the gas stream with additional cooling water circulated from a new cooling tower and (2) the addition of commercial air-conditioning type water chillers with their supporting cooling tower and water system to circulate chilled water through the existing tunnel cooler.

Method (1) has the advantage of providing additional cooling in the winter months when cooling tower water approaching chilled water temperature from chillers is available. It presents some additional tunnel pressure loss, but this is expected to be very small, since the added surface area would be located in the low velocity region of the tunnel circuit and low loss surface is available for this type of application.

Method (2) has a limitation on cooling capacity, since chiller water temperature below 40° to 45°F would not be attainable during either summer or winter periods. This would limit cooling capacity to about twice that presently available in hot weather, unless additional cooler surface area were also added in the tunnel circuit. In addition, added power charges would be incurred with this method.

It is recommended that additional cooling be provided if needed by adding surface area in the main circuit.

3. Cooling System Costs

Based upon recent quotes on large wind tunnel coolers and estimates for the costs of water piping, pumping and cooling tower, the installed cost for additional tunnel cooling would be approximately $100 per horsepower. This is based upon cooling water supplied at 85°F and a tunnel air temperature of 115°F. Increasing the main drive power from 20,000 to 30,000 hp would require a cooling system addition capable of handling an additional 10,000 hp and would cost about $1,000,000; while increasing main drive power to 50,000 hp would require an additional 30,000 hp cooling system at a cost of about $3,000,000.

C. CIRCUIT COMPRESSOR

1. General

The circuit fan or compressor system consists of 24 remotely adjustable prerotation vanes, a 47 blade fan, and 40 remotely adjustable stator vanes followed by 30 fixed stator vanes. Fan hub diameter is 25.2 feet and tip diameter is 36.0 feet. Additional equipment consists of the fan shaft, support bearings, nose fairing, drive section outer shell, shaft seals and couplings, support equipment, and lubrication system.

Tunnel performance improvement methods which do not include power addition to the main tunnel drive, such as an auxiliary compressor system or circuit loss reduction, are believed to require

only minor if any modification of the circuit compressor. However, those methods considered which do add drive power, such as rewinding the existing motor for 30,000 hp or replacement of the motor with one of 50,000 hp, may require appreciable modification of the compressor system.

Structural and mechanical design notes and computations for stress levels and sizing of the compressor system were not available for this study. Therefore, it was necessary to make what appeared to be reasonable assumptions with regard to the required modification work. Should the project proceed to the design phase, stress levels should be examined for the selected improvement method.

2. Increased Main Drive Power

a. Rewinding for 30,000 hp

It was expected that increasing the main drive power by rewinding the existing motor for 30,000 hp may result in a requirement for a new thrust bearing, new compressor blades, and perhaps new blade sockets to handle the additional blade loading that would occur with this repowering. All other components of the compressor system are expected to be capable of handling the additional loads that would be imposed. However, a detailed analysis of vanes, bearings, couplings, hub, and shafting would be required during a design phase for this modification.

b. Repowering for 50,000 hp

The loads imposed with a new drive system capable of providing 50,000 hp would be expected to require a completely new

compressor system. Approximately the same two compressor speeds, compressor diameters, and compressor pressure ratio would be retained along with the existing drive section outer shell.

3. Auxiliary Compressor System

The addition of an auxiliary compressor system external to the tunnel circuit imposes no additional loading on the fan blades or bearings. However, some additional load would be imposed on the circuit compressor system vanes. It is expected that this would not be sufficient to necessitate modification of these components.

4. Tunnel Pressurization

Increased tunnel total pressure capability, by itself, would not appear to be warranted since little or no performance improvement would be obtained. When combined with one of the performance improvement methods mentioned above, additional circuit compressor loading would occur as indicated by that method, and modification work would be needed as indicated. Venting and pressurizing of seals in the drive system might have to be modified somewhat in order to accommodate the increased pressure in the tunnel.

D. GAS CHARGING SYSTEM

1. General

As indicated earlier in this report, the TDT is operated most of the time with Freon-12 of about 95% purity. Air is used as the test medium at other times. Methods and equipment are presently available for charging the tunnel with either test medium. This equipment is also used for evacuating and/or charging the test section

independently of the rest of the circuit, so as to permit personnel entry for model changes and adjustments in an atmosphere of air at sea level pressure.

Increased pressurization of the tunnel circuit is required in order to improve dynamic pressure capability at the lower Mach numbers, with many of the methods considered. Therefore, a study was made for modifications that might be required to the gas charging system in order to cope with increased tunnel pressure. A limit of 1.25 times the present upper operating pressure of 2,500 psfa was deemed adequate to take advantage of the performance improvement methods considered and to stay within reasonable tunnel shell pressure capability.

2. Freon System

Freon is stored in a liquid receiver with a pressure capability of over 100 psia and supplied to the tunnel in gaseous form through a vaporizer. The system is deemed adequate, from a pressure capability standpoint, to supply the tunnel at operating pressures at least up to the proposed limit. Addition of liquid storage capacity might be warranted for some of the methods being considered due to the increased quantity of freon used for charging the tunnel at the higher pressures.

3. Air System

Air is supplied to the tunnel from atmosphere through filters, silencer, and dryer and, depending on tunnel pressure, to the tunnel circuit either through compressors or directly. Compressor capability for the proposed pressure appears to be adequate.

4. Other Considerations

The time required to perform certain pumping or charging operations would be greater than at present for going from one extreme to the other, since the extremes would now be further apart. However, the time for performing the same functions as at present would not change. Refer to Table I in Langley Working Paper 799 which gives the length of time required for performing these operations:

a. Convert tunnel from air at atmospheric pressure to freon at from 100 to 2,100 psfa.

b. Start tunnel after model change completed, freon in tunnel at from 100 to 2,100 psfa.

c. Make entry to test section after tunnel shutdown, freon in tunnel at from 100 to 2,100 psfa.

d. Same as a, b and c above but with air in tunnel.

e. Time required to vary total pressure in the tunnel from 100 to 2,100 psfa with both air and freon.

Assuming that the present time requirements for performing these tunnel operations are acceptable, it does not appear that the increased pressure for some of the methods being considered would make operating times unacceptable.

E. ELECTRICAL POWER SUPPLY

The existing electric power system at the Langley Field installation is supplied by the Virginia Electric Power Company through the Stratton Road Substation located in the West Facilities area at 115,000 volts. All power load additions require that power correction

equipment be included to maintain a 95 to 98% power factor operating condition of this supply. The use of synchronous motor drive equipment for compressors operating at one constant speed, where possible in utilization equipment, will help reduce corrective equipment additions. It was assumed that no increased total maximum power requirement would be needed from the power supply company by proper scheduling of power demand.

The East Facilities area receives its power supply from the above substation by means of one underground pipe-type cable operating at 110,000 volts and two underground cables operating at 22,000 volts. The underground pipe-type cable to the Back River Substation in the east area has a total capability of approximately 94 mva that would be adequate to supply electric power to the tunnel drive system and auxiliaries of all studies covered in this report.

The entire 41.6 mva maximum capability of the transformer "1D", located in Back River Substation, can be made available by transferring 22,000 volt underground cables and scheduling test periods of other tunnel loads connected to this transformer. For modifications involving the addition of an auxiliary compressor system and/or the rewinding of the existing motor for 30,000 hp, this would serve as the power source. Auxiliary equipment and miscellaneous requirements would be supplied from the 22,000 volt system. The necessary reactive power correction equipment and switching facilities would be located adjacent to this transformer with existing utilization voltage equipment.

The modification involving the replacement of the existing drive system with one capable of 50,000 hp would require the addition of a new power transformer of approximately 50 mva to step down the cable supply voltage to a utilization voltage of 13,800 volts. Associated reactive power corrective equipment and switching equipment would be located adjacent to this transformer. An underground duct and manhole system with cables would be required to the tunnel drive system, protective relaying and tunnel control system areas.

VI CONCLUSIONS

Based upon the study work performed for the TDT, the following conclusions have been reached:

1. Virtually all of the possible methods to improve the performance of the TDT for increased dynamic pressure and Mach number have been considered.

2. Many of the methods considered are not believed to be feasible for technical reasons or for prohibitive cost and downtime in terms of the performance gain possible.

3. Several promising methods were explored in some detail for performance improvement, cost, and tunnel downtime. Results are presented in this report.

4. In terms of performance gain per dollar of expenditure, the most promising method may be a reduction of circuit losses, based upon experimental verification. However, the magnitude of improvement is expected to be limited. For a very significant performance improvement, rewinding of the main drive motor appears to offer the most economical approach.

5. For the possible modification methods considered, the performance improvement, costs, and tunnel downtime were estimated as follows:

Method	Approximate Performance Improvement %	Cost	Tunnel Downtime
1. Rewind drive for 30,000 hp	50	$ 2,800,000	2-3 mos.
2. New 50,000 hp drive	150	11,500,000	6 mos.
3. 10,000 hp Auxiliary Compressor System (freon only)	50	6,000,000	3-4 mos.
4. Same as above, but air and freon	50	9,600,000	3-4 mos.
5. Rewind drive for 30,000 hp plus Auxiliary System of 15,000 hp, freon only	150	9,100,000	3-4 mos.
6. Same as 5 above, but for air and freon	150	12,800,000	3-4 mos.
7. Circuit Loss Reduction	*	50,000	*

* Variable and limited

VII RECOMMENDATIONS

The following recommendations are provided to improve the performance of the TDT:

1. Conduct the circuit loss experimental work as proposed in this report and assess the improvement possible. Modify the circuit to reduce losses as warranted by the results of this work.

2. Initiate a preliminary design phase of work for one of the major improvement methods outlined in this report. The selected method should be that which provides the required magnitude of performance improvement together with acceptable cost and tunnel downtime. The preliminary design work should detail all of the modification work in terms of components, site locations, methods of construction, types of equipment, costs, and design and construction schedules.

3. Proceed to final design in order to prepare detailed plans and specifications for the construction work.

APPENDIX A

TABLES

TABLE 1

TDT CIRCUIT LOSS ELEMENT PHYSICAL CHARACTERISTICS

Section	Station	Type Loss	Area, ft²	Deq, ft	2θ, °	K_T (FIXED	D_H, ft	L, ft	Sect. D_H, AVG
1	E191	Expansion	394.6	22.41	7.6	0.0264	8.12	59	11.49
1a	E132	Expansion	718.0	30.23	12.3	0.0564	14.86	55	22.13
2	E77	Screen	1394	42.13	—	1.60	29.40	—	—
3	E75	Expansion	1422	42.55	12.6	0.0116	29.88	25	38.96
4	E50	Expansion	1813	48.05	6.5	0.0052	48.05	50	50.90
5	E0	Corner + Cooler	2269	53.75	—	1.00	53.75	—	—
6	S5	Corner	2214	53.09	—	0.22	—	—	—
7	W0	Contraction	2214	53.09	—	—	53.09	44	34.80
8	W44	Test Section	241.1	17.52	—	—	16.50	36	16.56
9	W80	Expansion	245.2	17.67	5.8	0.0034	16.63	16	13.92
9a	—	Shock + Flap Loss	f(MACH)	—	—	f(MACH)	—	—	—
10	N96	Expansion	271.0	19.28 / 13.32	1.1	0.0003	11.20	13	11.29
11	W109	Expansion	289.0	13.56	2.0	0.0020	11.38	20	15.78
12	W129	Expansion	319.6	20.17 / 14.26	6.5	0.0380	20.17	85	24.97
13	W214	Corner	695.8	29.76	—	0.22	29.76	—	—
14	N0	Expansion	695.8	29.76	6.5	0.0057	29.76	33	31.62
15	N33	Corner + Screen	880.4	33.48	—	0.60	33.48	—	—
16	E212.5	Contraction	795.0	31.82	—	—	23.28	18.5	16.34
17	E194	Fan (Rise)	447.4	23.87	—	—	9.40	—	—

NOTES: (1) REFER TO 10/17/72 work for equations, ect.
(2) ON Station, E, W, ect. refers to East, West. ect.
(3) Two sets of dimensions at stas 10, & 12 are required to consider effect of strut upon corresponding elements.

TABLE I

TABLE 2

SUMMARY OF TDT PRESSURE LOSS CALCULATIONS; AIR

	P_t = 2000		P_t = 750		P_t = 540		P_t = 400		P_t = 350		P_t = 300	
SECTION	M = 0.4		M = 0.7		M = 0.9		M = 1.0		M = 1.1		M = 1.2	
	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%
1	4.8	9.6	4.2	9.7	3.5	7.9	2.9	6.7	2.5	4.9	2.2	3.5
1a	1.6	3.2	1.3	3.1	1.1	2.4	0.9	2.0	0.8	1.5	0.6	1.0
2	8.9	17.8	7.1	16.6	5.7	12.6	4.6	10.7	4.9	7.8	3.4	5.4
3	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0	0
4	0.1	0.1	0	0	0	0	0	0	0	0	0	0
5	2.1	4.2	1.7	3.9	1.4	3.0	1.1	2.6	0.9	1.8	0.8	1.3
6	0.5	1.0	0.4	0.9	0.3	0.7	0.2	0.6	0.2	0.4	0.2	0.3
7	0.6	1.1	0.6	1.3	0.5	1.2	0.4	1.0	0.4	0.8	0.3	0.5
8	5.9	11.8	5.9	13.7	5.6	12.5	5.1	11.9	4.9	9.7	4.6	7.3
9	1.9	3.8	1.9	4.4	2.6	5.8	2.3	5.4	2.2	4.4	2.0	3.2
9a	0	0	0	0	4.7	10.4	9.1	21.3	20.5	40.0	35.6	56.8
10	1.3	2.6	1.2	2.8	1.1	2.4	0.9	2.2	0.9	1.7	0.8	1.3
11	1.5	3.1	1.4	3.3	1.4	3.2	1.2	2.8	1.1	2.2	1.0	1.6
12	6.8	13.6	6.0	13.8	7.9	17.5	6.6	15.3	5.9	11.6	5.3	8.5
13	5.0	10.0	4.0	9.4	3.2	7.2	2.7	6.2	2.4	4.7	2.1	3.3
14	0.3	0.6	0.3	0.6	0.2	0.5	0.2	0.4	0.2	0.3	0.1	0.2
15	8.5	17.0	6.9	16.0	5.5	12.3	4.5	10.6	4.1	7.9	3.6	5.7
16	0.2	0.3	0.2	0.3	0.1	0.3	0.1	0.2	0.1	0.2	0.1	0.1
Totals	50.1	100	43.2	100	44.9	100	42.9	100	51.2	100	62.7	100
λ_C	1.026		1.060		1.095		1.115		1.163		1.248	
λ_T	1.009		1.022		1.048		1.066		1.111		1.191	
λ_B	1.009		1.021		1.025		1.025		1.025		1.025	
λ_R	1.007		1.016		1.019		1.020		1.021		1.023	
ER	4.01		4.30		3.75		3.49		2.76		2.04	
q_c:	105,890		157,060		174,390		177,810		183,050		190,400	
POWER	7.12		8.97		10.19		9.81		11.65		14.10	
η_c	61.9		51.1		61.2		58.4		68.3		80.8	

TABLE 3

SUMMARY OF TDT PRESSURE LOSS CALCULATIONS; FREON

SECTION	P_t=2200 M=0.4		P_t=2200 M=0.7		P_t=1300 M=0.9		P_t=1100 M=1.0		P_t=950 M=1.1		P_t=700 M=1.2	
	ΔP_T	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%
1	3.8	9.5	7.9	8.9	6.3	7.0	5.5	5.8	4.8	4.5	3.4	2.8
1a	1.3	3.3	2.8	3.1	2.1	2.4	1.9	2.0	1.6	1.5	1.1	0.9
2	7.4	18.6	15.9	17.9	12.2	13.6	10.5	11.1	9.0	8.4	6.2	5.3
3	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
4	0	0	0.1	0.1	0.1	0.1	0	0	0	0	0	0
5	1.7	4.2	3.8	4.3	2.9	3.2	2.5	2.6	2.2	2.0	1.5	1.2
6	0.4	1.0	0.9	1.0	0.7	0.7	0.6	0.6	0.5	0.5	0.3	0.3
7	0.4	1.0	1.0	1.1	0.9	1.0	0.9	0.9	0.8	0.7	0.6	0.6
8	4.3	10.8	10.5	11.8	9.9	11.0	9.6	10.0	9.2	8.5	7.5	6.4
9	1.7	4.2	3.5	4.0	5.2	5.7	4.9	5.2	4.7	4.3	3.7	3.1
9a	0	0	0	0	9.0	10.0	22.4	23.6	43.1	40.2	70.4	59.5
10	0.9	2.3	2.1	2.4	1.9	2.1	1.7	1.8	1.5	1.4	1.2	1.0
11	1.1	2.8	2.6	2.9	2.6	2.9	2.4	2.5	2.1	2.0	1.6	1.4
12	5.4	13.5	12.2	13.8	16.5	18.2	14.6	15.3	12.8	11.9	9.5	8.0
13	4.1	10.3	9.1	10.2	7.2	7.9	6.3	6.6	5.5	5.1	4.0	3.4
14	0.2	0.5	0.5	0.6	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2
15	7.0	17.6	15.4	17.4	12.2	13.5	10.6	11.2	9.3	8.6	6.8	5.7
16	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
TOTALS	39.9	100	88.7	100	90.4	100	95.1	100	107.6	100	118.2	100
λ_C	1.020		1.046		1.073		1.092		1.123		1.192	
λ_T	1.007		1.016		1.036		1.053		1.083		1.150	
λ_B	1.008		1.016		1.020		1.020		1.020		1.018	
λ_R	1.006		1.013		1.016		1.017		1.017		1.018	
ER	4.15		4.76		4.23		3.81		3.16		2.28	
Q_C:	47,775		71,450		79,410		81,275		82,520		83,800	
POWER	2.56		8.40		9.38		10.00		11.25		11.94	
η_C	40.3		44.8		53.1		56.8		64.1		68.4	

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. 4 OF

DATE 5/28/73

COMPUTATIONS FOR

BY CHKD

TABLE 4

AUXILIARY SYSTEM DUCTING CHARACTERISTICS

element	Type loss	Area, ft²	Diam., ft	L, ft.	2θ°	Loss Coeff.
1	contraction	262.47	18.29	10	45	0.05
2	90° corner	78.54	10.00			0.15
3	PIPE	78.54	10.00	100		
4	90° corner	78.54	10.00			0.15
5	Diverging Branch	78.54	10.00			1.00
6	PIPE	44.18	7.50	28		
7	90° corner	44.18	7.50			0.15
8	valve	44.18	7.50			0.25
9	screen	44.18	7.50	β=80%		0.25
10	expansion	44.18	7.50	10		0.04
11	COMP. INLET	63.00	D_H = 8.96			
12	expan + resist	23.76	5.50	3	45.2	0.16
13	cooler	50.26	8.00			3.00
14	contraction	50.26	8.00	3	45.2	0.001
15	valve	23.76	5.50			0.25
16	90° corner	23.76	5.50			0.15
17	60° corner	23.76	5.50			0.15
18	Conv. Branch	23.76	5.50			0.36
19	pipe	44.18	7.50	35		
20	90° corner	44.18	7.50			0.15
21	PIPE	44.18	7.50	110		
22	90° corner	44.18	7.50			0.15
23	PIPE	44.18	7.50	40		
24	90° corner	44.18	7.50			0.15
25	PIPE	44.18	7.50	130		
26	30° corner	44.18	7.50			0.15
27	PIPE	44.18	7.50	45		
28	90° corner	44.18	7.50			0.15
29	expansion	44.18	7.50	9	5.5	0.015
30	sudden expan.	~55.00	D_H = 8.37			1.00
31	REENTRY PLENUM	~500.0				

TABLE 5

FREON OPERATION
COMPARISON OF POSSIBLE MODIFICATIONS, SHELL
PRESSURE AND MACH NUMBER

Main Drive hp	Main Drive Current Load	Auxiliary Compressor Sys. - hp	% Present Structural Limit of Tunnel Shell	Full Power Utilization Available for Mach Nos. Above
20,000	Normal	none	100 (2500 psfa)	0.5
20,000	Overload	none	100	0.6
20,000	Normal	10,000	100	0.6
20,000	Overload	10,000	100	0.7
30,000	Normal	none	100	0.7
30,000	Overload	none	100	0.8
30,000	Normal	15,000	125 (3125 psfa)	0.7
30,000	Overload	15,000	125	0.8
50,000	Normal	none	125	0.85
50,000	Normal	none	150 (3750 psfa)	0.75

APPENDIX B

FIGURES

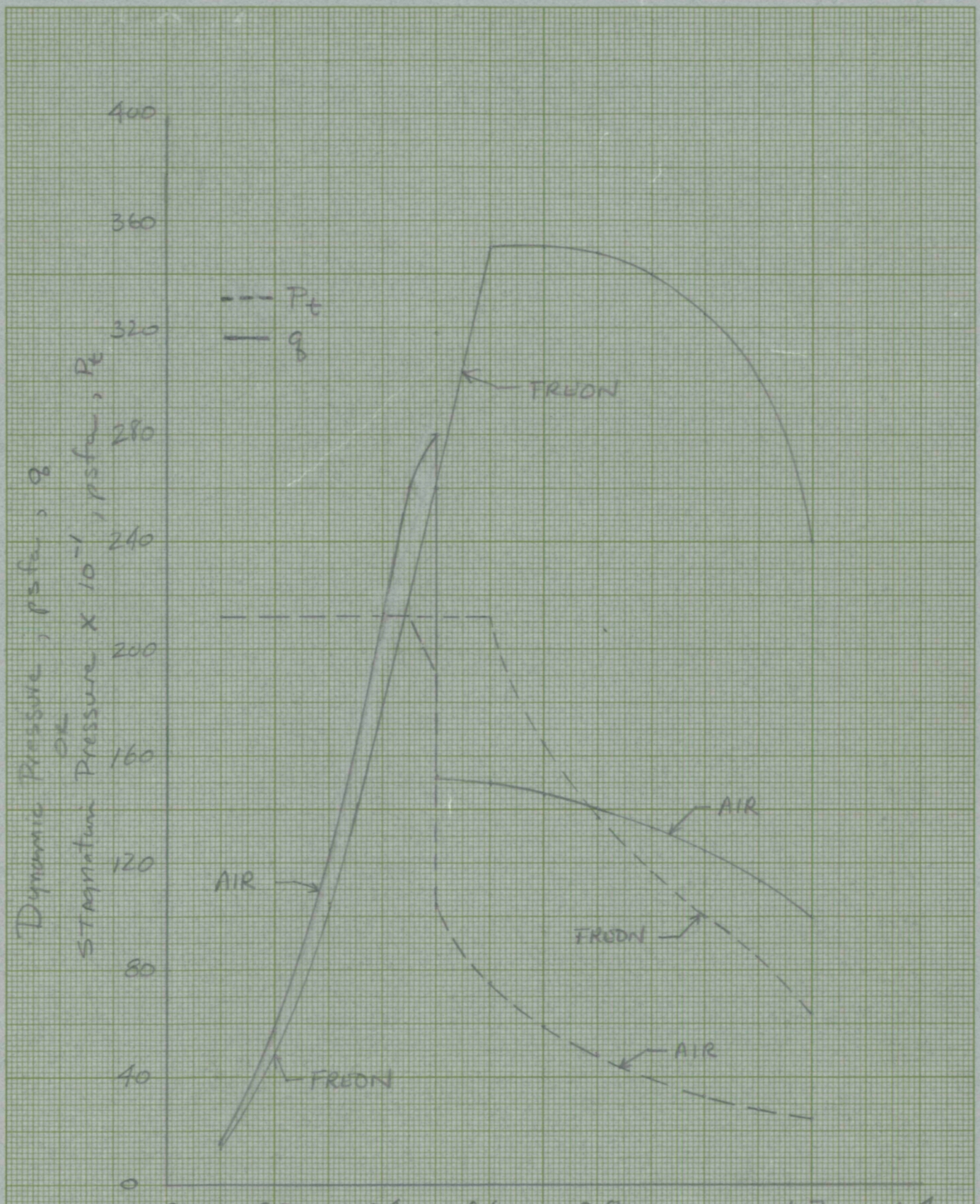

Fig 1. TDT Maximum Dynamic and Total Pressure at rated power.

EUGENE DIETZGEN CO.
MADE IN U. S. A.
NO. 340A-M DIETZGEN GRAPH PAPER
MILLIMETER

TTO
5/15/73

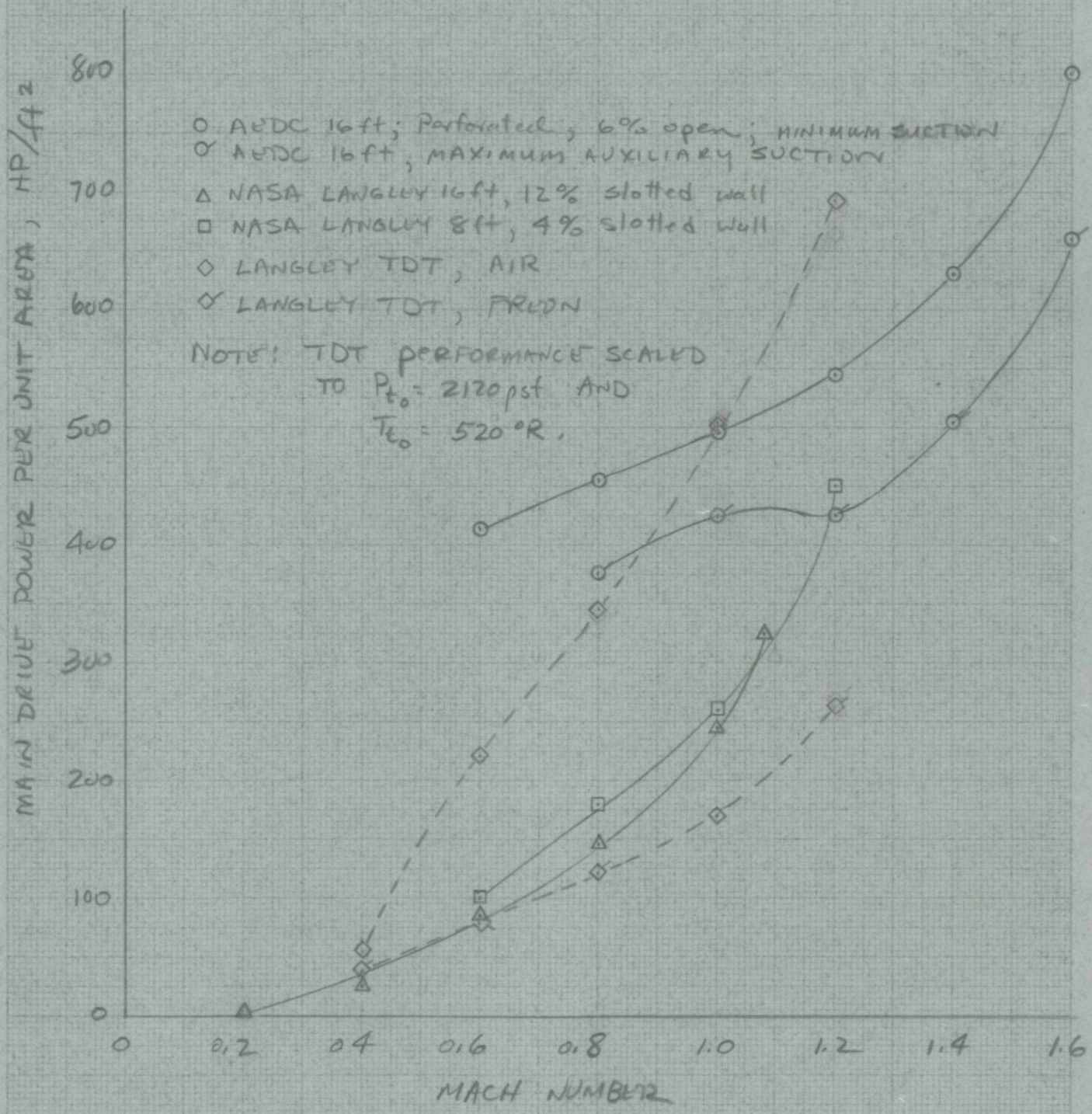

Fig 2. Main Drive Power Requirements for Various Large Scale Wind Tunnels.

FRT 5/15/73

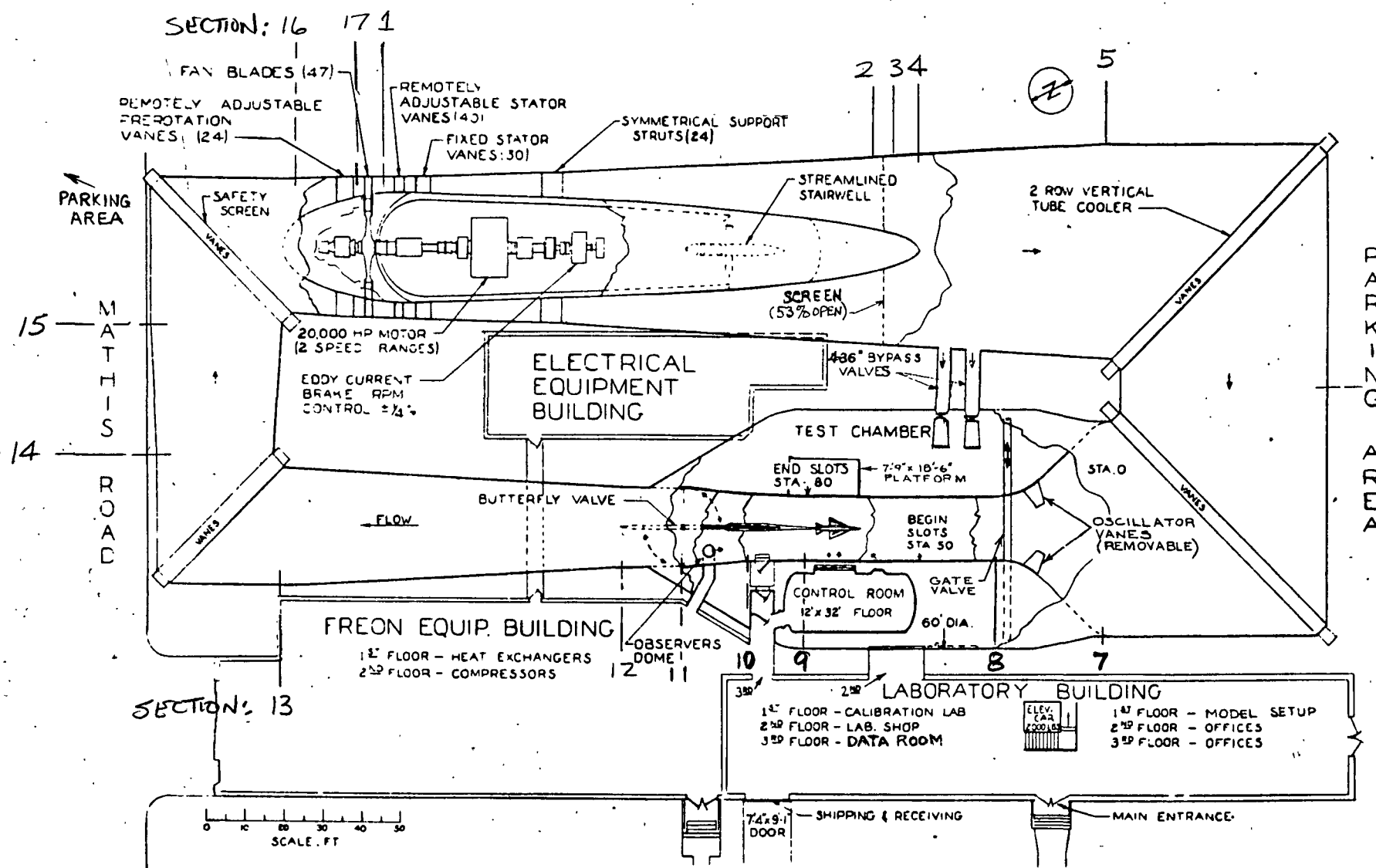

FIGURE 2.- GENERAL ARRANGEMENT OF THE LANGLEY TRANSONIC DYNAMICS TUNNEL

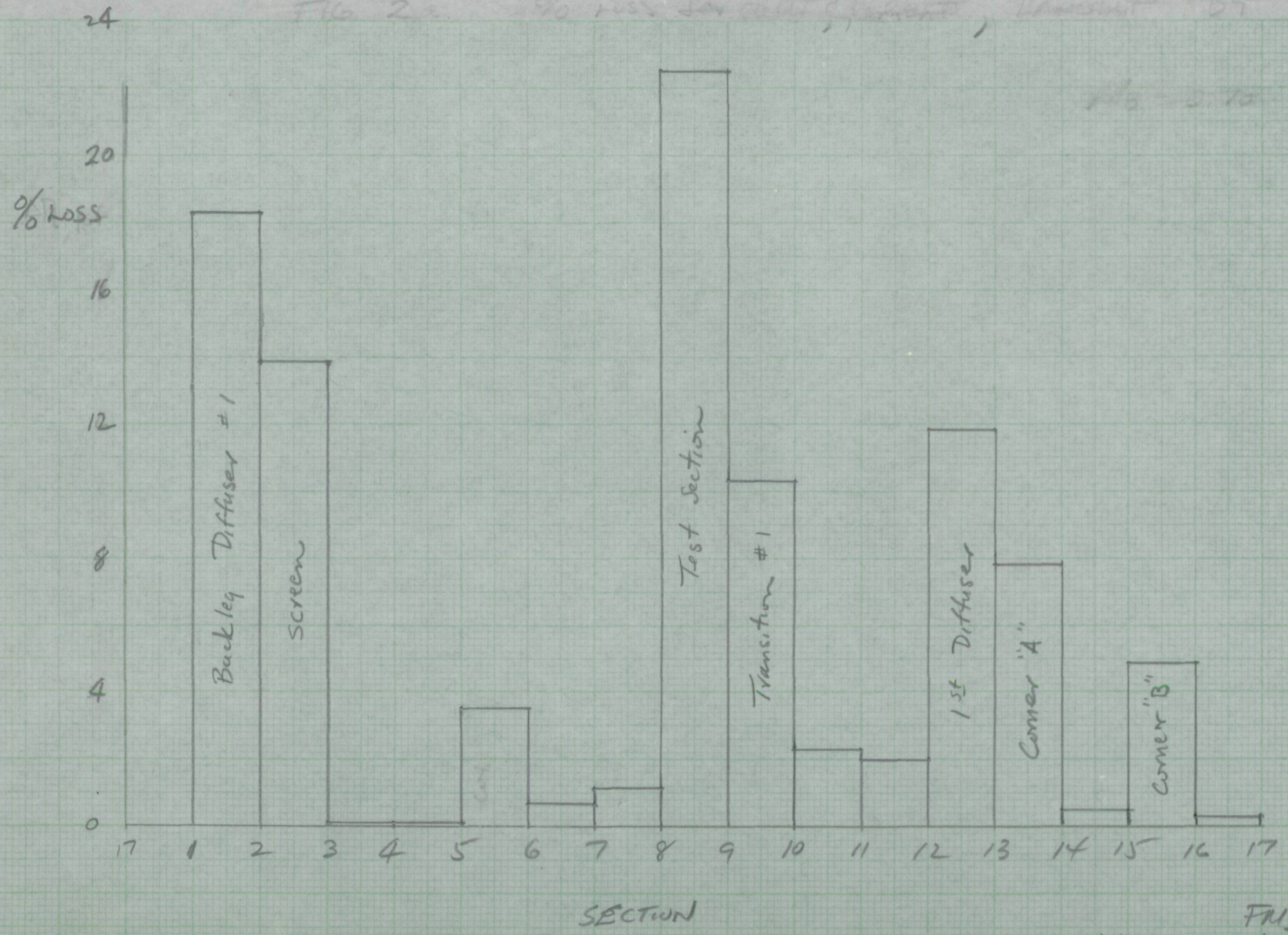

Fig 4. Percent Pressure Loss for Various TDT circuit Elements at $M_{\infty} = 0.70$, AIR.

FRJ
10/19/72

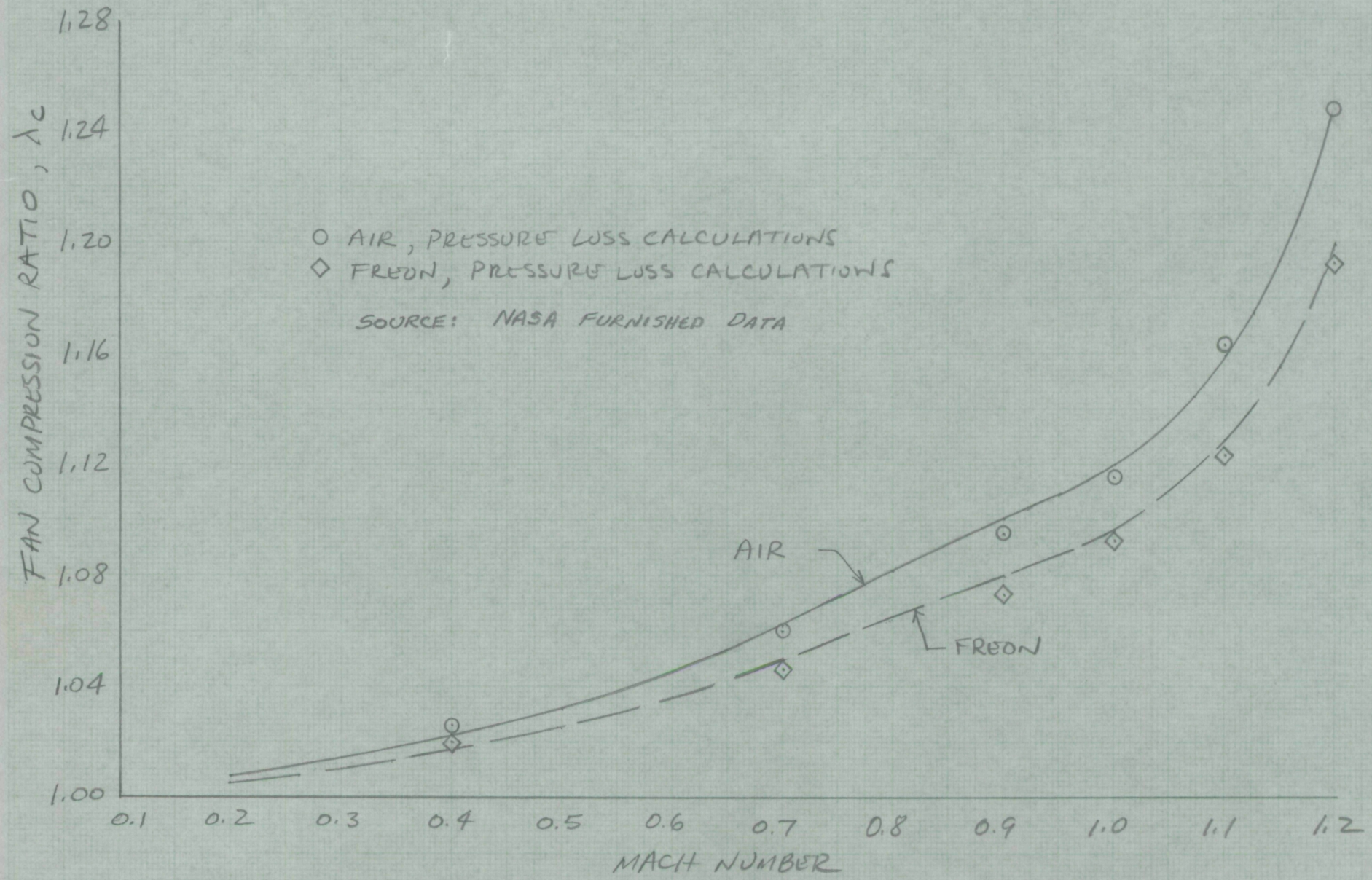

Fig 5 The Langley TDT FAN Compression RATIO

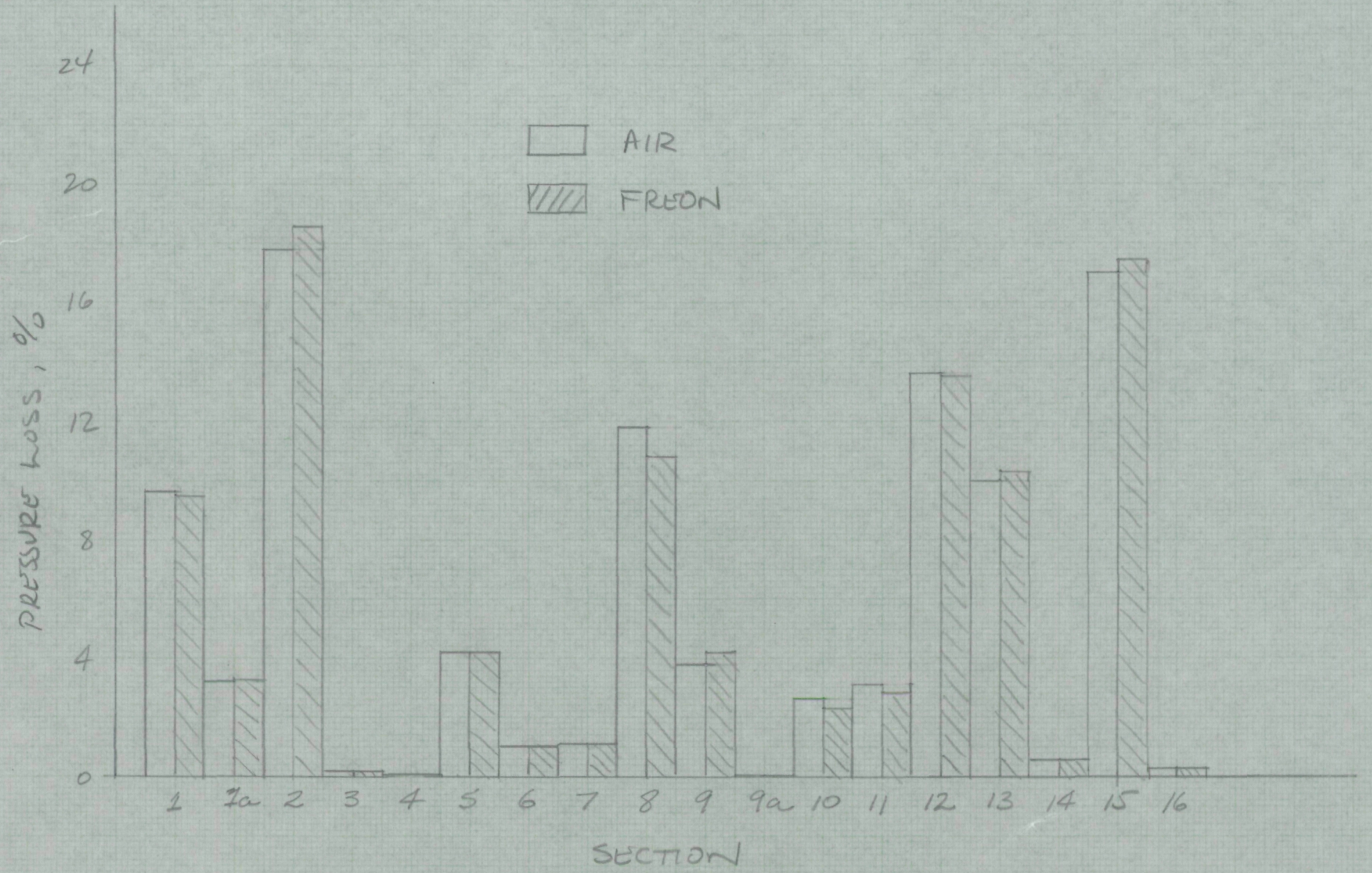

Fig. 6 Pressure Loss of Various Elements of the Langley TDT at $M_\infty = 0.4$ and maximum power.

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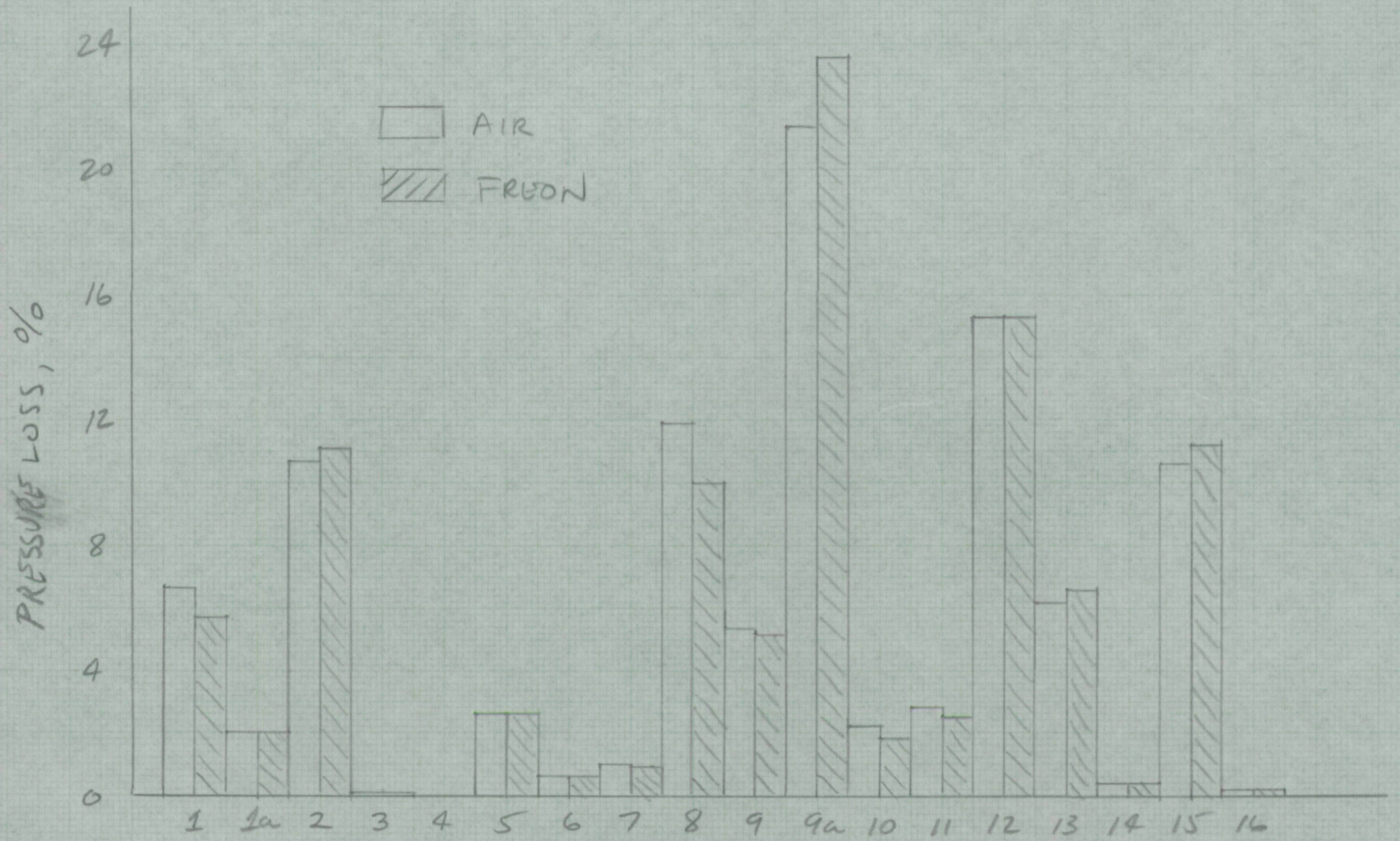

FIG 7 Pressure Loss of Various Elements of the Langley TDT at $M_\infty = 1.0$ and MAXIMUM power.

EMJ
5/15/73

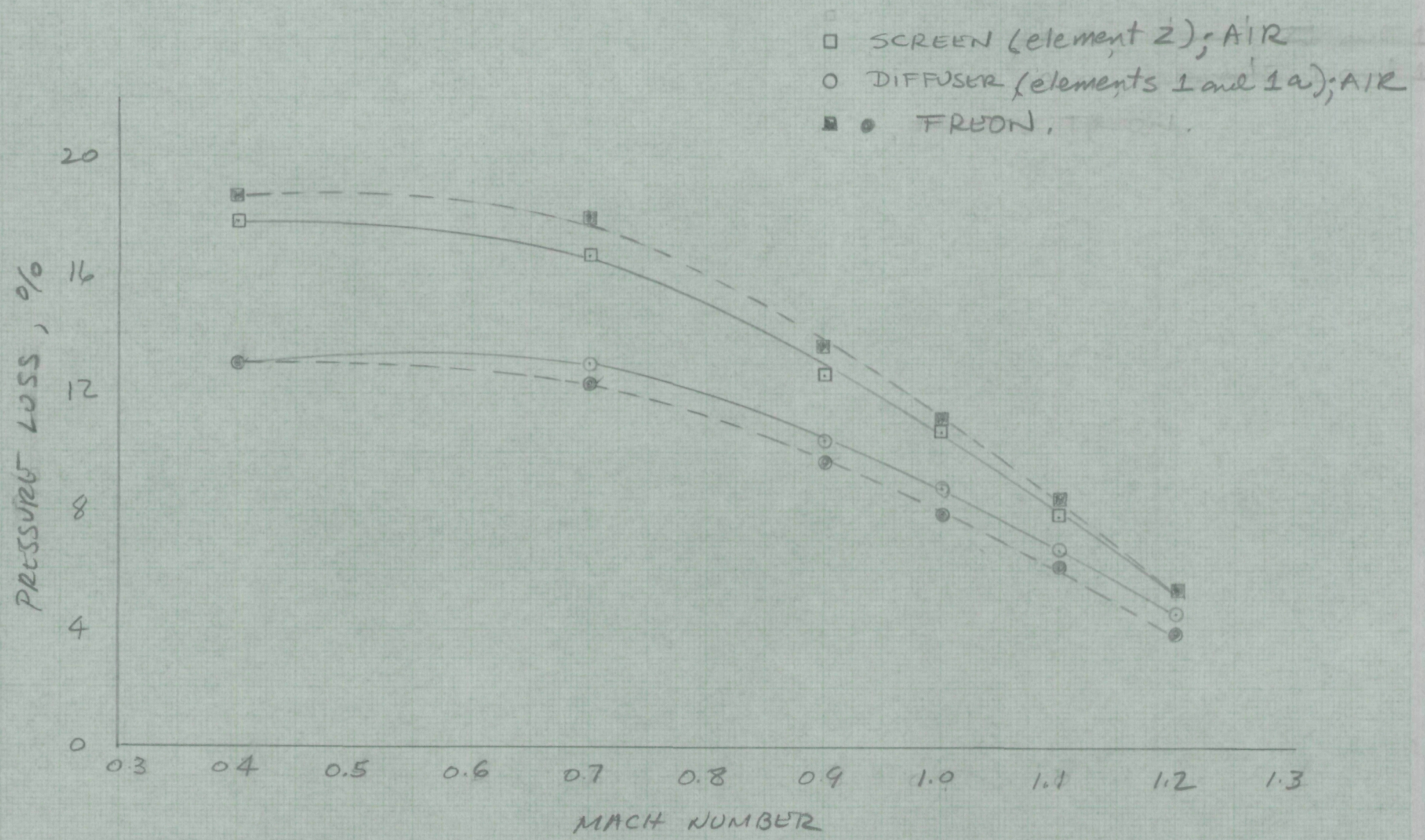

FIG. 8 Pressure Loss of the LANGLEY TDT East Leg Diffuser and Screen at various Mach numbers.

5/15/73
FMJ

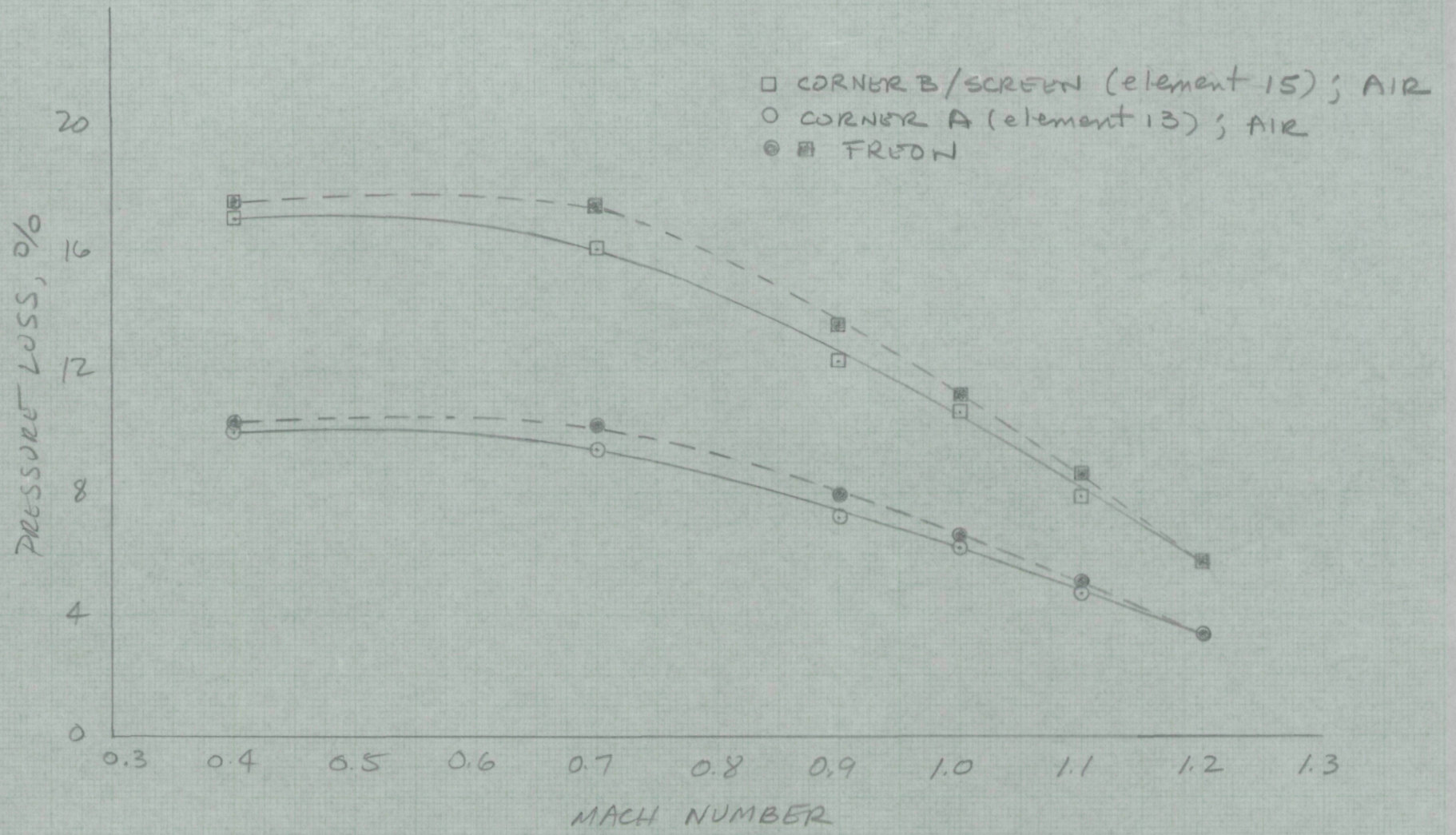

Fig 9. Pressure Loss of the LANGLEY TDT CORNER "A" and CORNER "B" at Various Mach Numbers.

FMJ
5/15/73

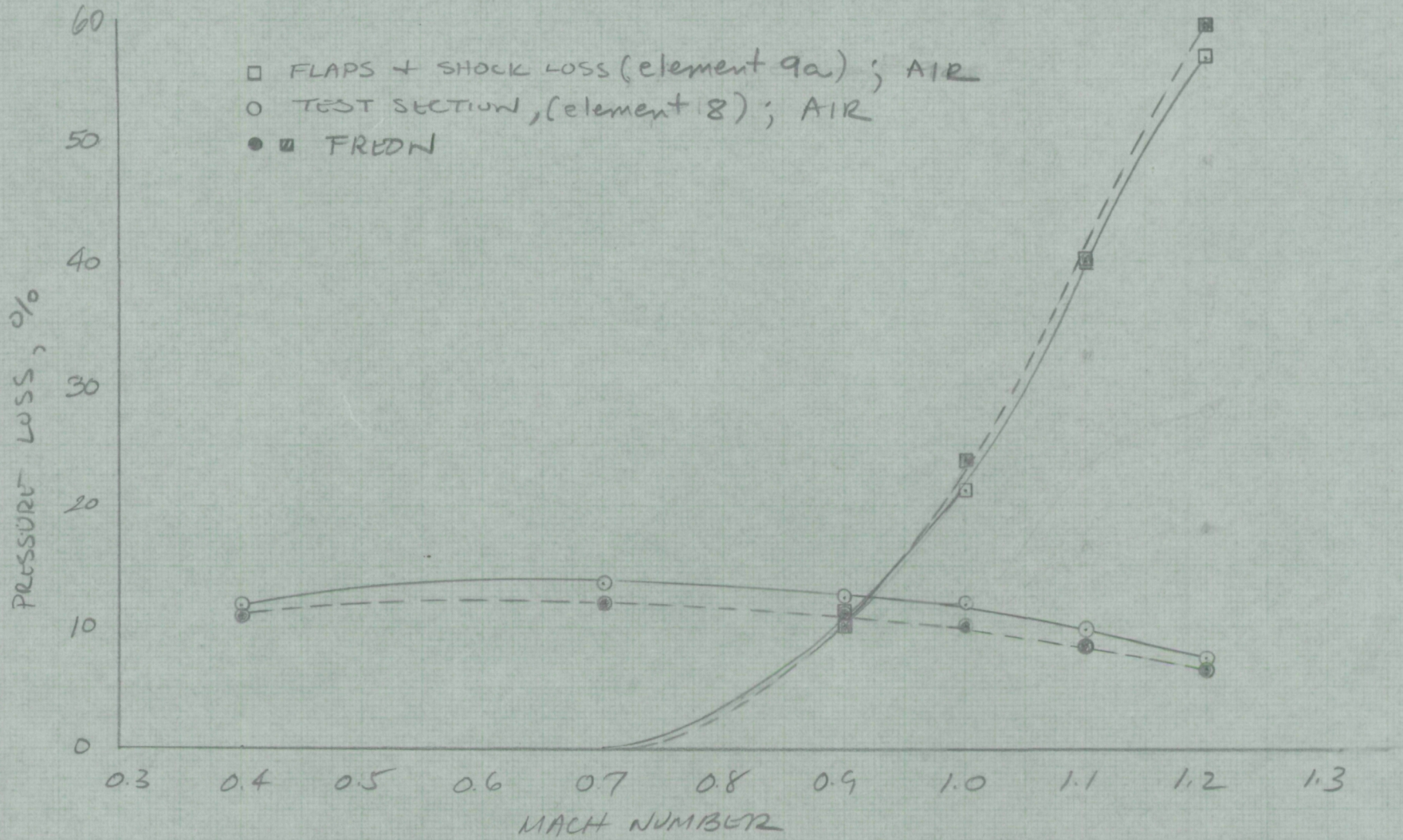

Fig 10 Pressure Loss of the LANGLEY TDT TEST SECTION AND FLAPS at VARIOUS MACH NUMBERS.

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5/15/93

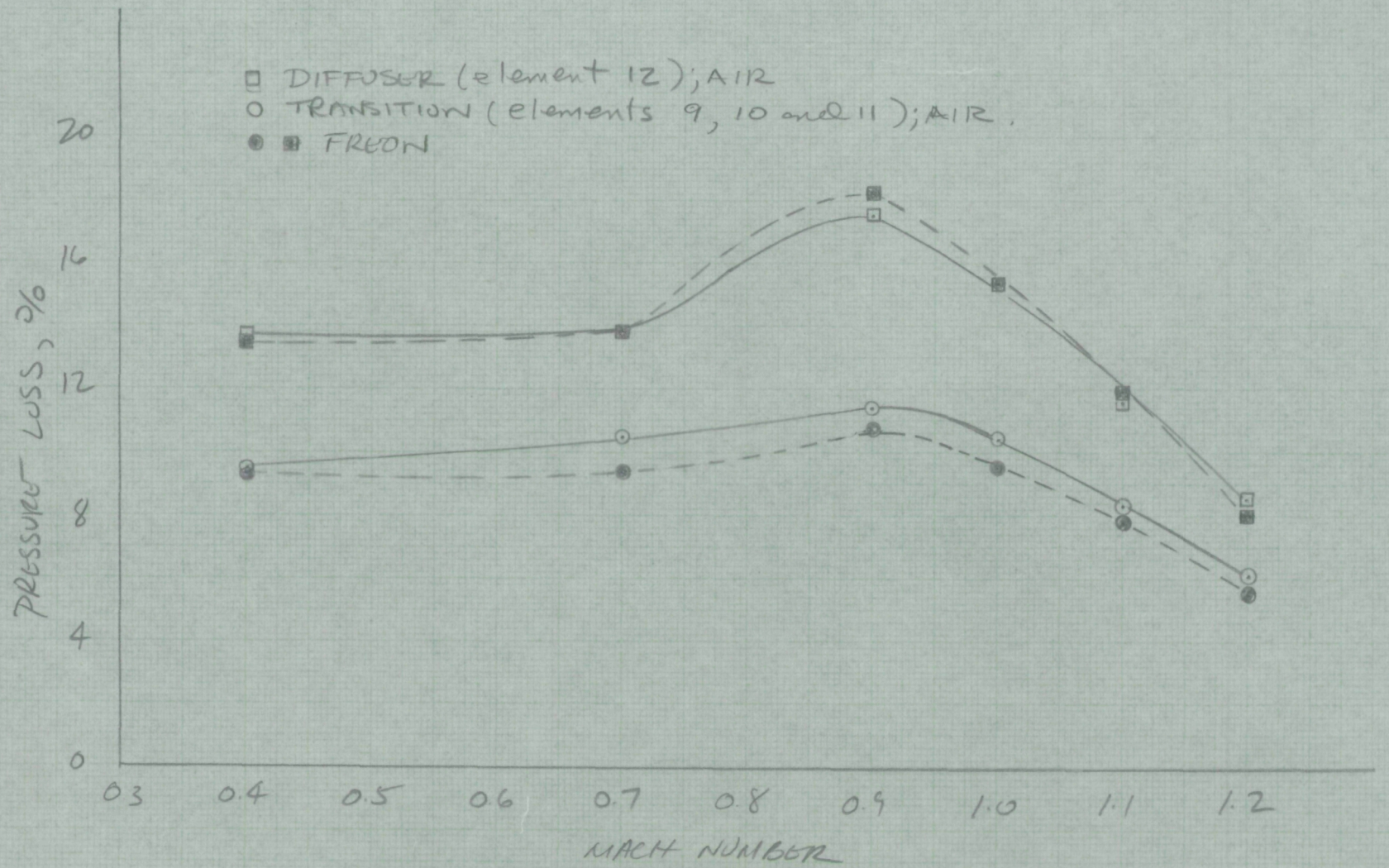

Fig. 11 Pressure Loss of the LANGLEY TDT West Leg Diffuser and Transition at various Mach Numbers.

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5/15/73

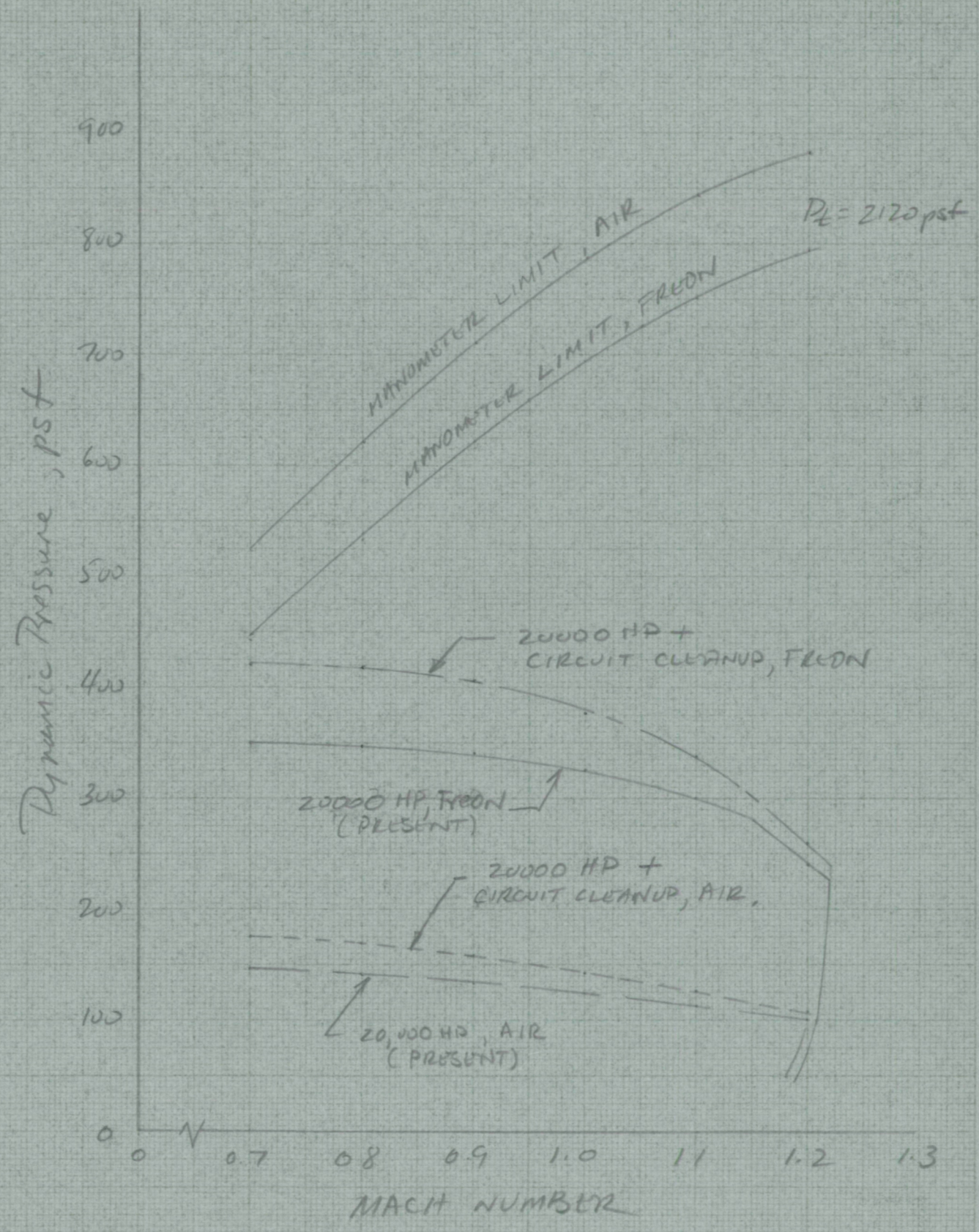

FIG 12. ESTIMATED TDT Performance for Complete Circuit Cleanup with 20,000 HP main DRIVE.

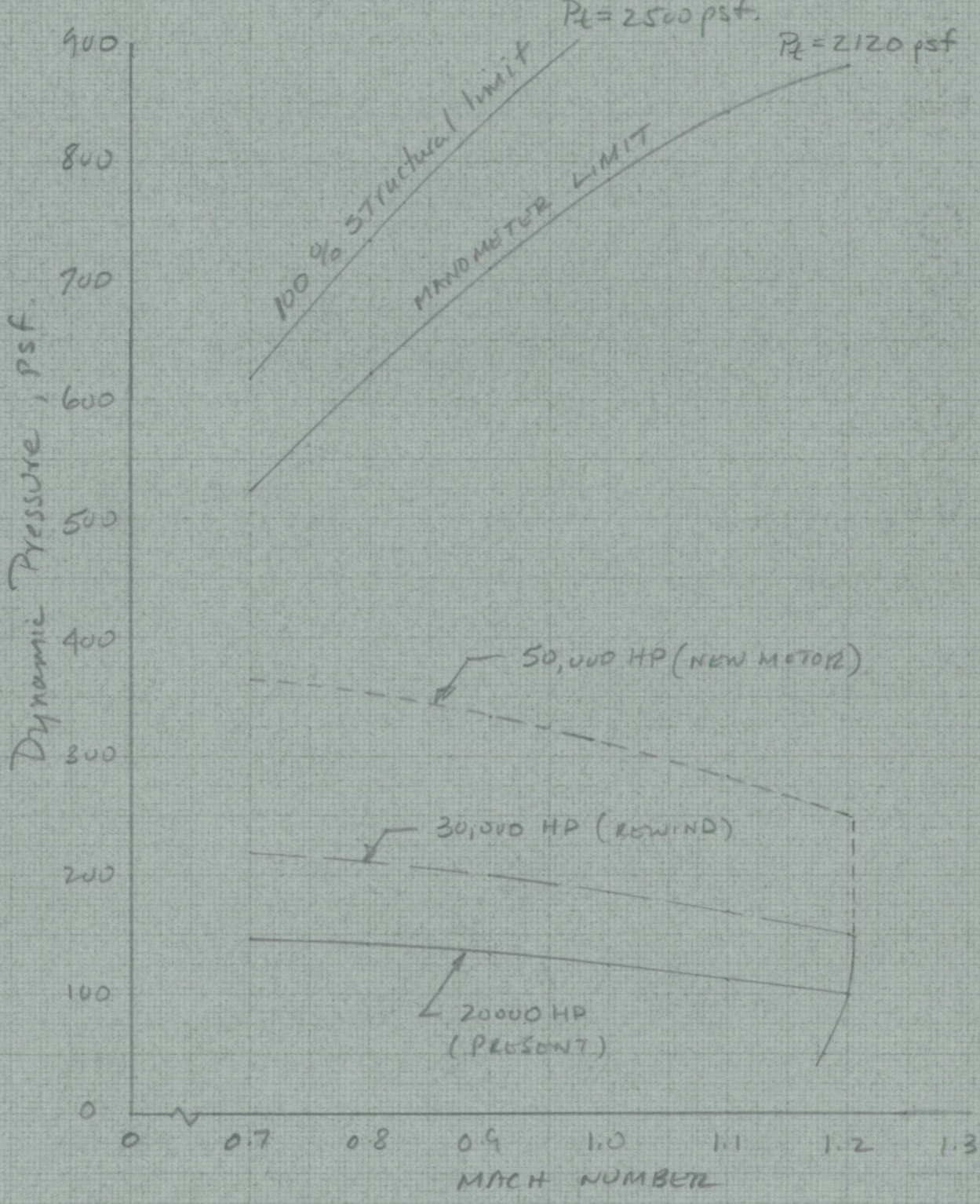

Fig 13, Estimated TDT Performance with Air for Proposed Main Drive Modifications

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5/28/73

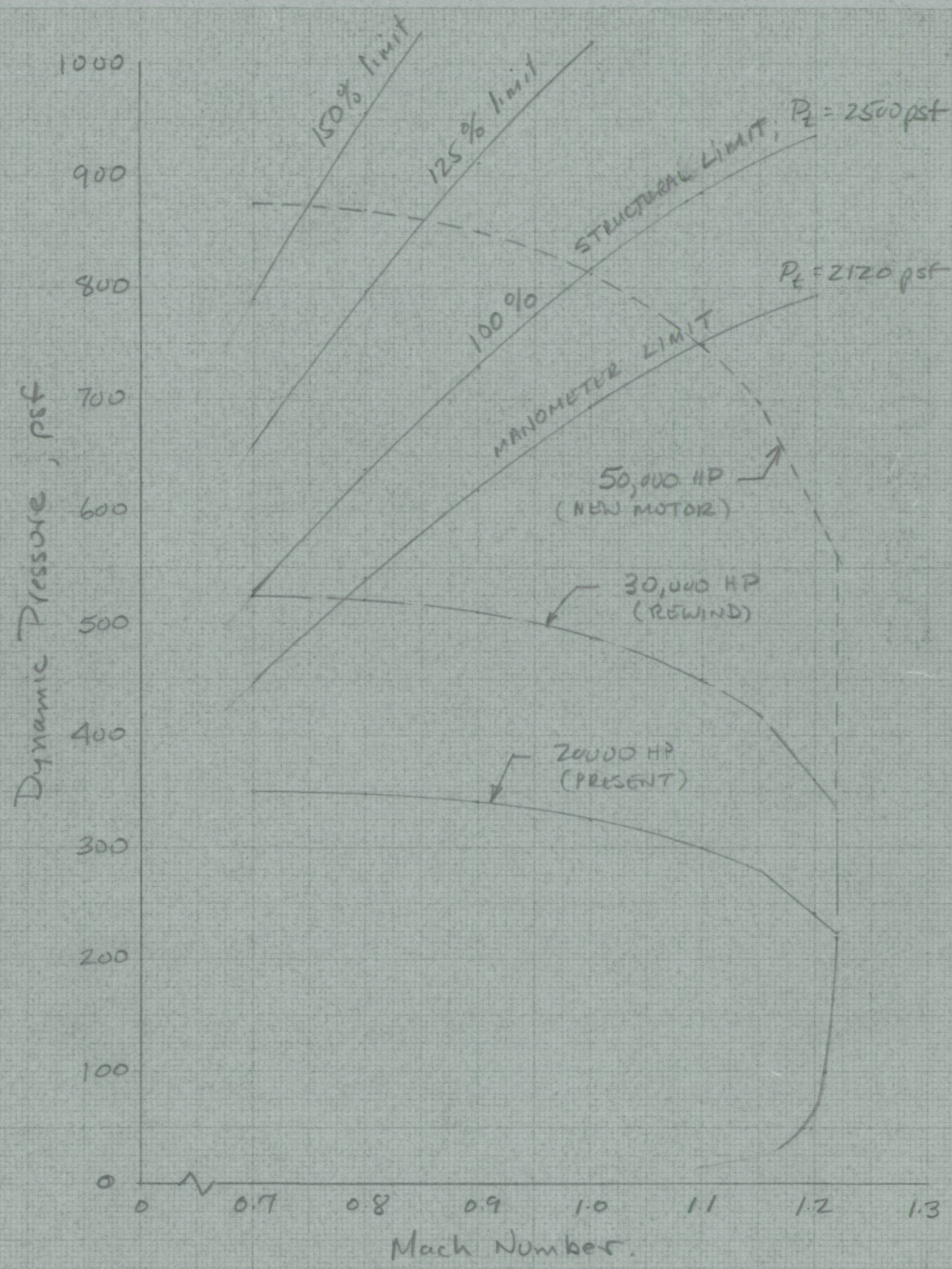

Fig. 14 Estimated TDT performance with Freon for proposed Main Drive Modifications

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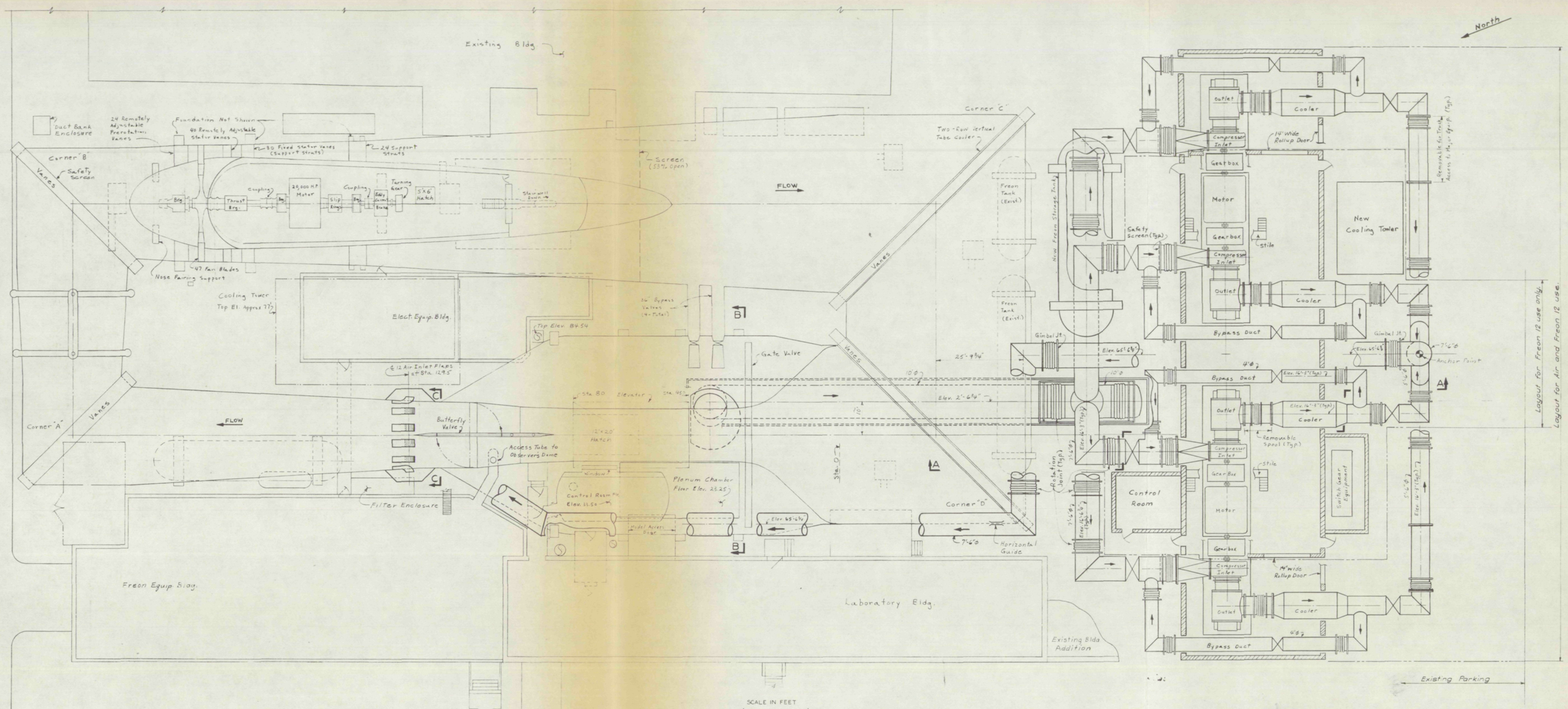


NO.	DATE	REVISION	BY	CK.	APPROVED

NASA - LANGLEY FIELD

TRANSONIC DYNAMICS TUNNEL
LOCATION PLAN OF NEW
AUXILIARY COMPRESSOR SYSTEM

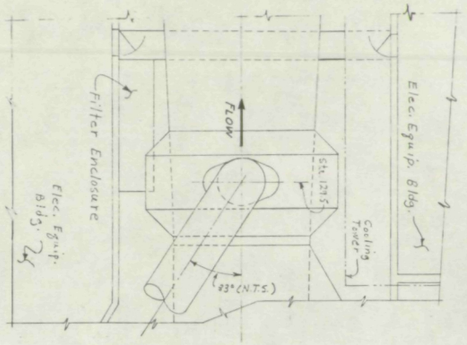
SVERDRUP & PARCEL AND ASSOCIATES, Inc.
ENGINEERS — ARCHITECTS
ST. LOUIS, MO.

SUBMITTED: SVERDRUP & PARCEL AND ASSOCIATES, INC.		APPROVED:	DATE:
VICE PRESIDENT			
SCALE:	TRACED:	FIGURE NO. 15	
DESIGNED: RHW	CHECKED:		
DRAWN: RHW	DATE: JUNE 1978		

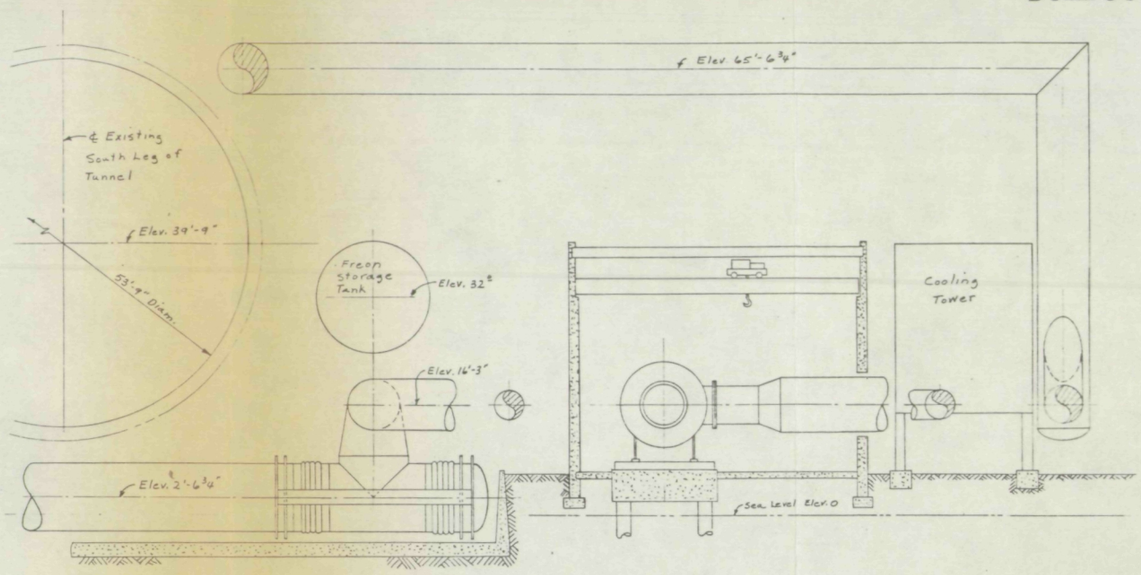
FOLDOUT FRAME 1
FOLDOUT FRAME 2
FOLDOUT FRAME 3

FOLDOUT FRAME 1

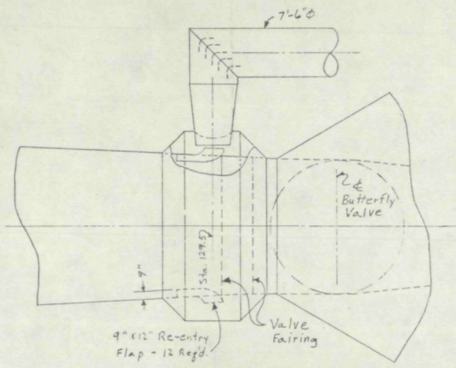
FOLDOUT FRAME 2



SECTION E-E



SECTION A-A



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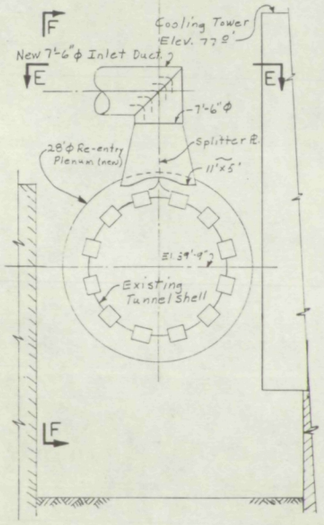
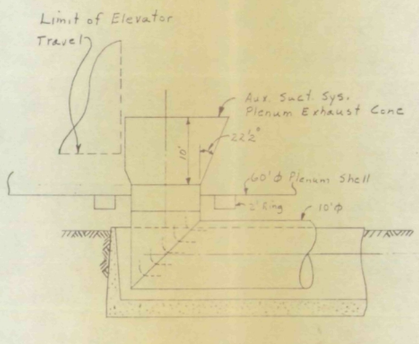
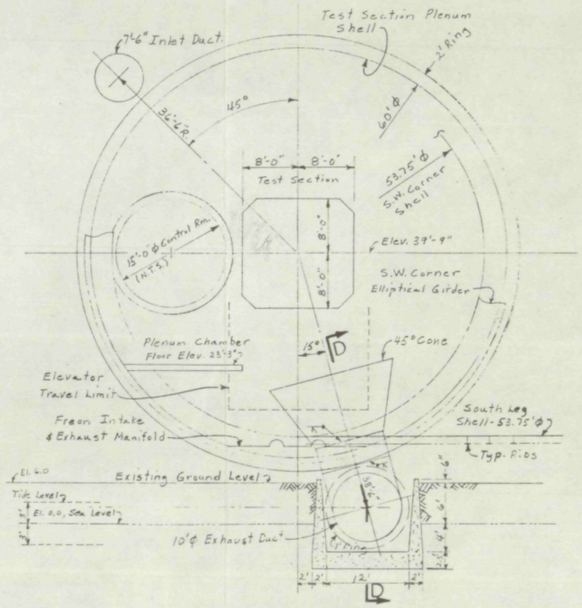


SECTION C-C



SECTION D-D



SECTION B-B

PAGE 72

SCALE IN FEET
10' 0 10'

NO.	DATE	REVISION	BY	CH.	APPROVED

NASA - LANGLEY FIELD

TRANSONIC DYNAMICS TUNNEL
DETAILS OF NEW
AUXILIARY COMPRESSOR SYSTEM

SVERDRUP & PARCEL AND ASSOCIATES, INC.
ENGINEERS — ARCHITECTS
ST. LOUIS, MO.

SUBMITTED: Sverdrup & Parcel And Associates, Inc. APPROVED: DATE:
Vice President

SCALE:	TRACED:	FIGURE NO. 15a
DESIGNED: RHW	CHECKED:	
DRAWN: RHW	DATE: JUNE 1973	

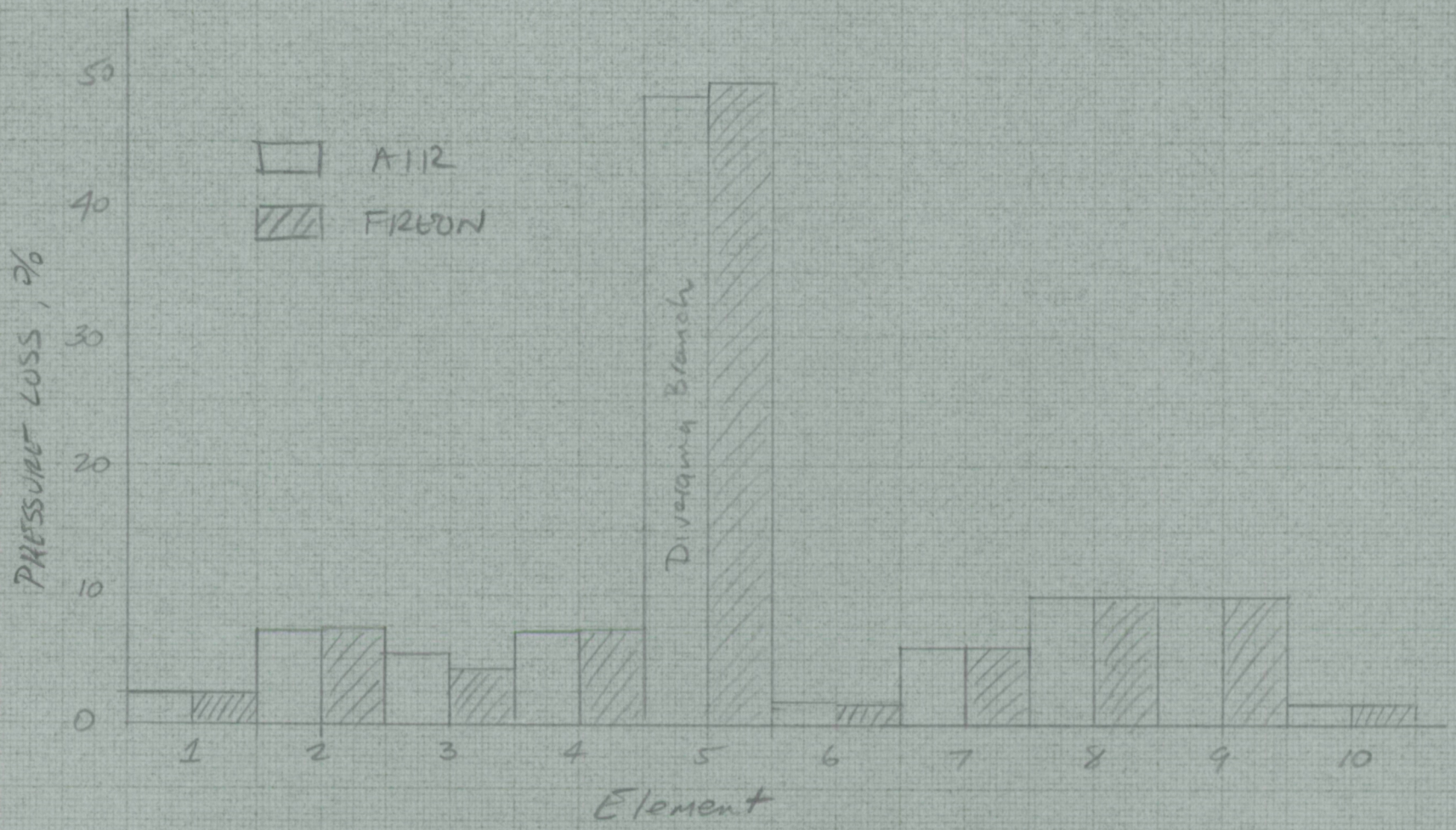


Fig 16 Pressure Loss of various elements of the Auxiliary System Inlet Ducting, $M_\infty = 1.2$ and $W_a/W_T = 0.05$

5/30/73
FMJ

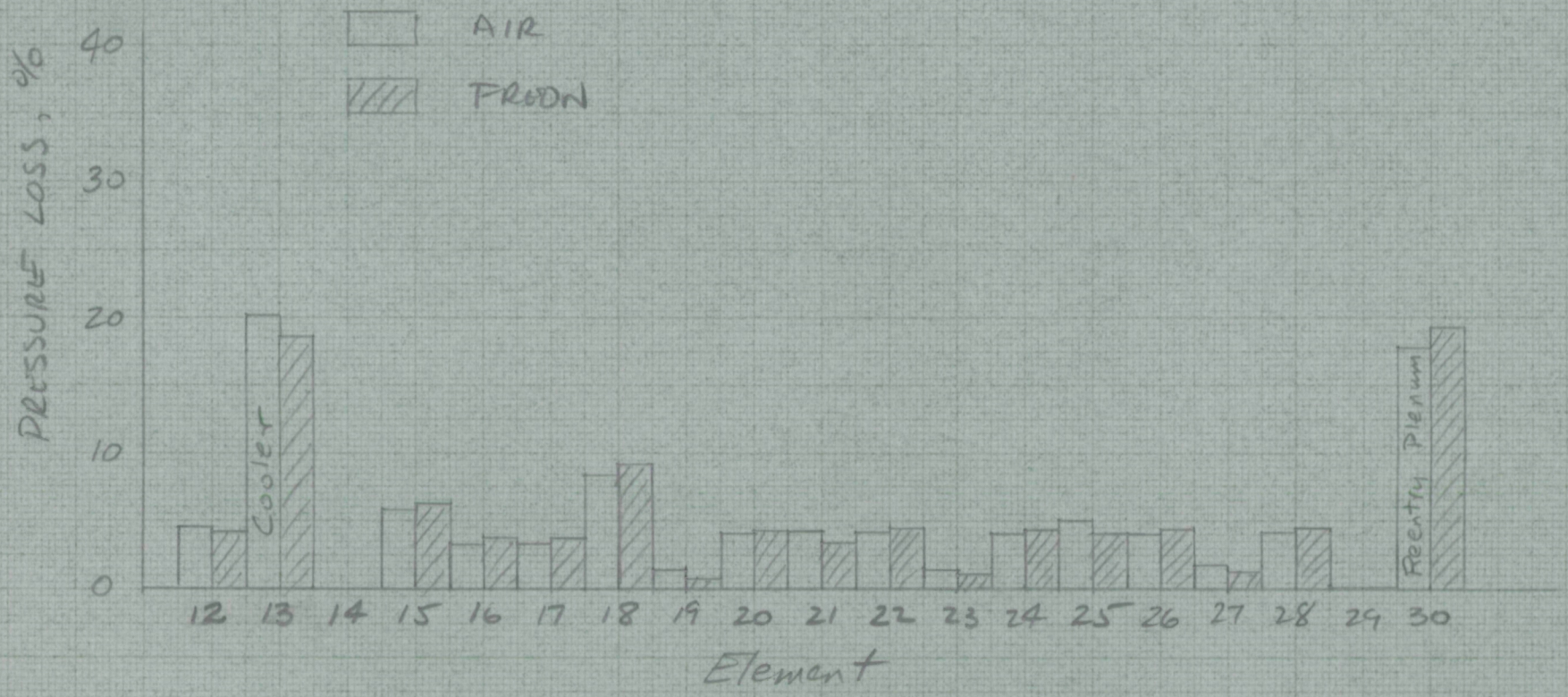


Fig 17. Pressure Loss of Various elements of the Auxiliary System Exit Ducting; $M_{\infty} \cong 1.2$, $w_a/w_T = 0.05$.

FMJ
5/30/73

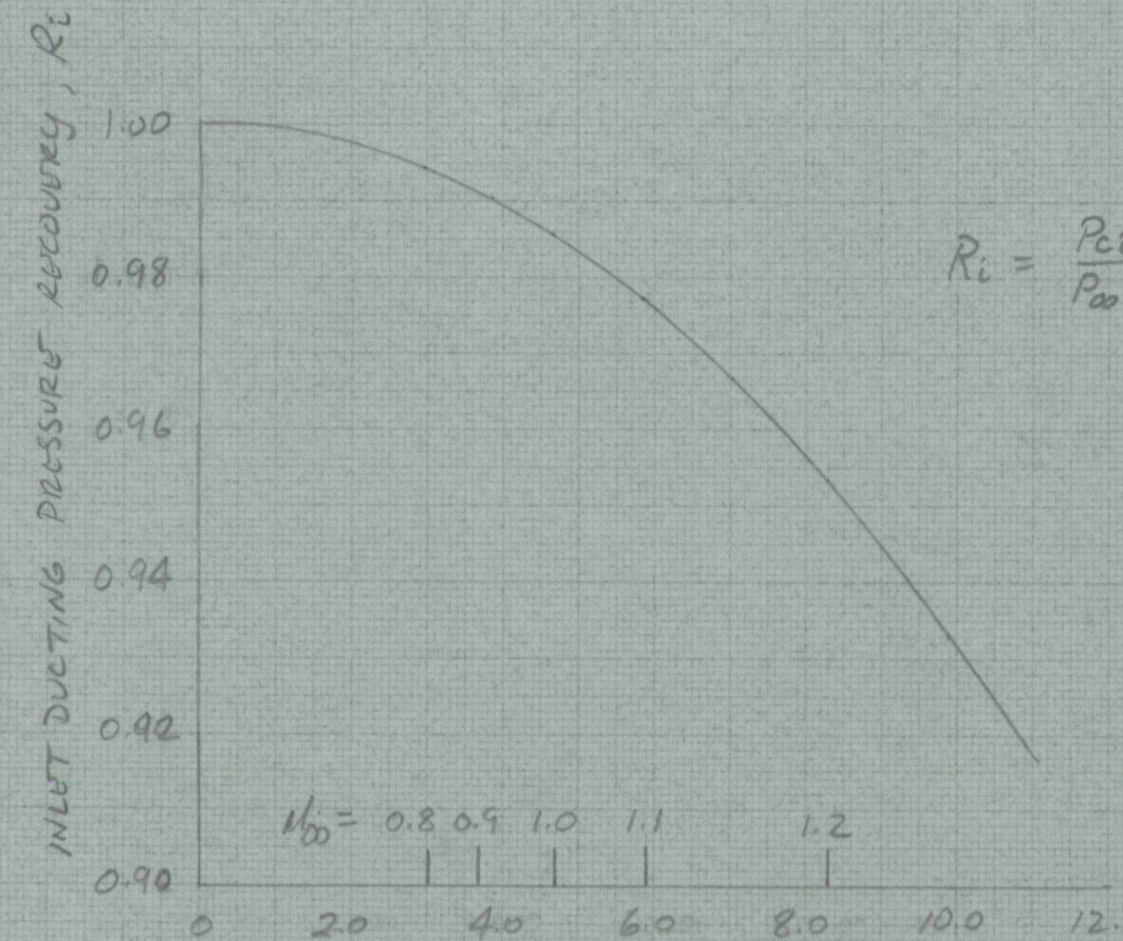
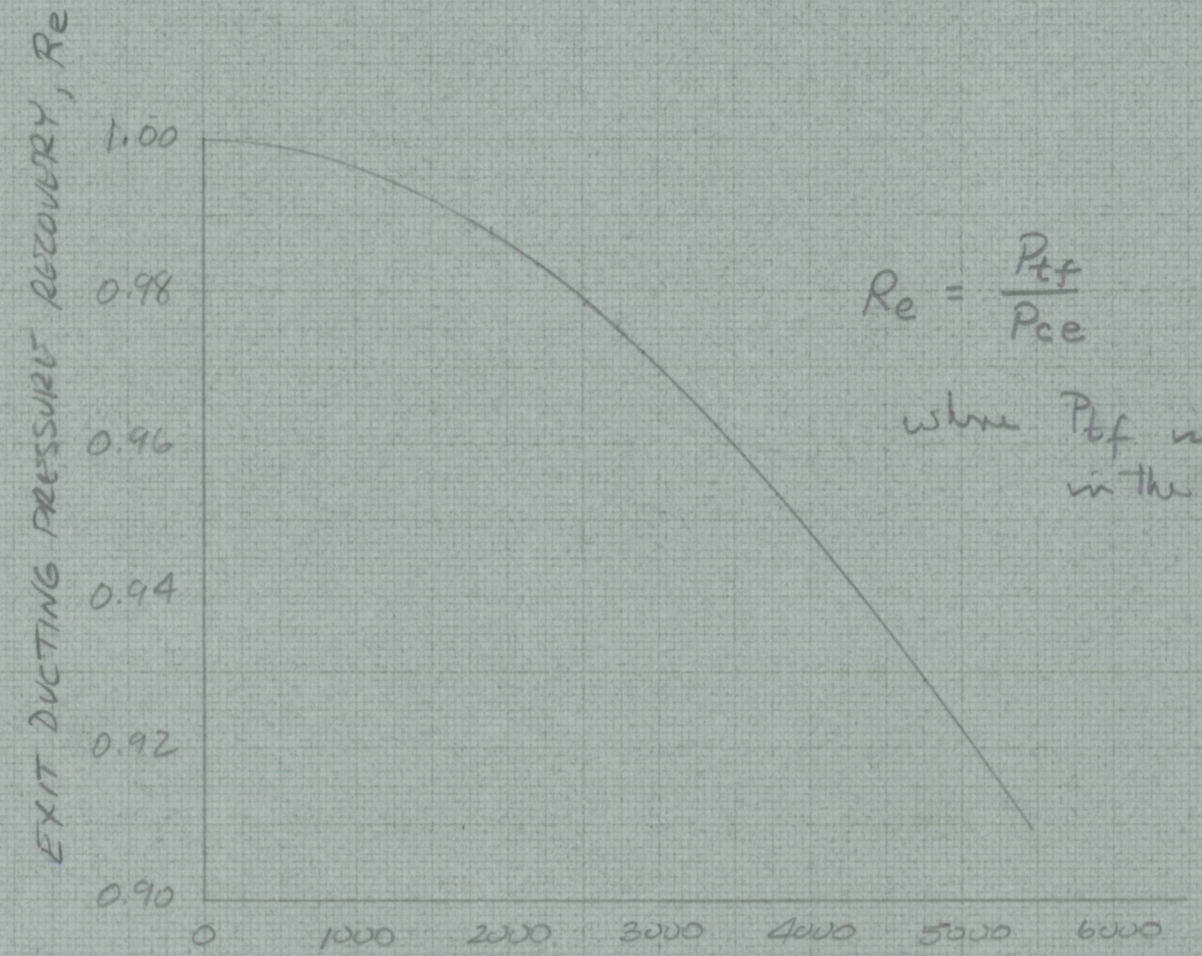


Fig 18 Pressure Recovery of the Auxiliary System Inlet Ducting with Freon as a test medium.

TJH 5/30/73



$$Re = \frac{P_{tf}}{P_{ce}}$$

where P_{tf} is the pressure in the reentry plenum.

FIG 19. Pressure Recovery of the Auxiliary System Exit Ducting with Freon as a Test Medium

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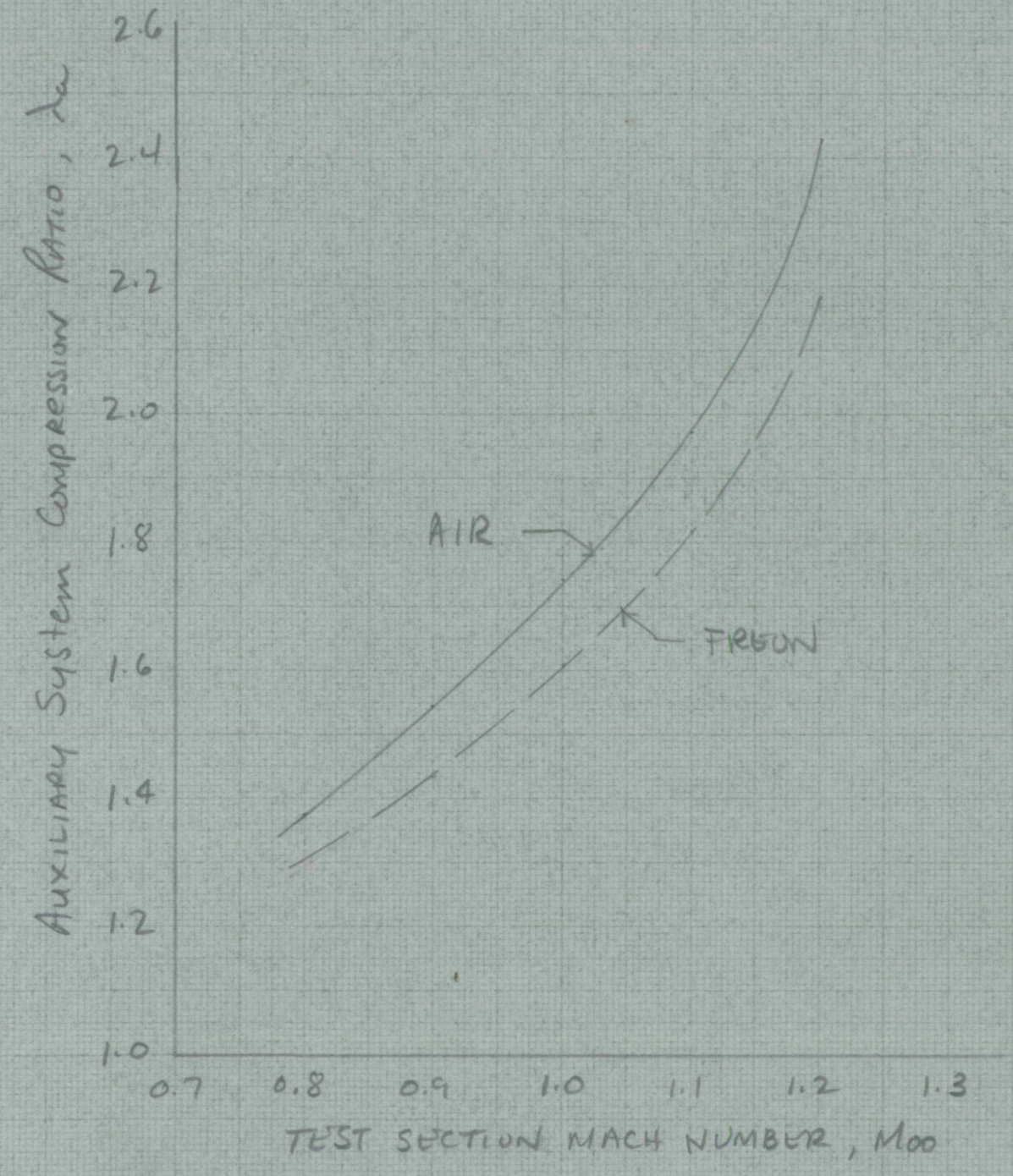

Fig 20. Auxiliary System Compressor Pressure Ratio Requirements.

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5/30/73.

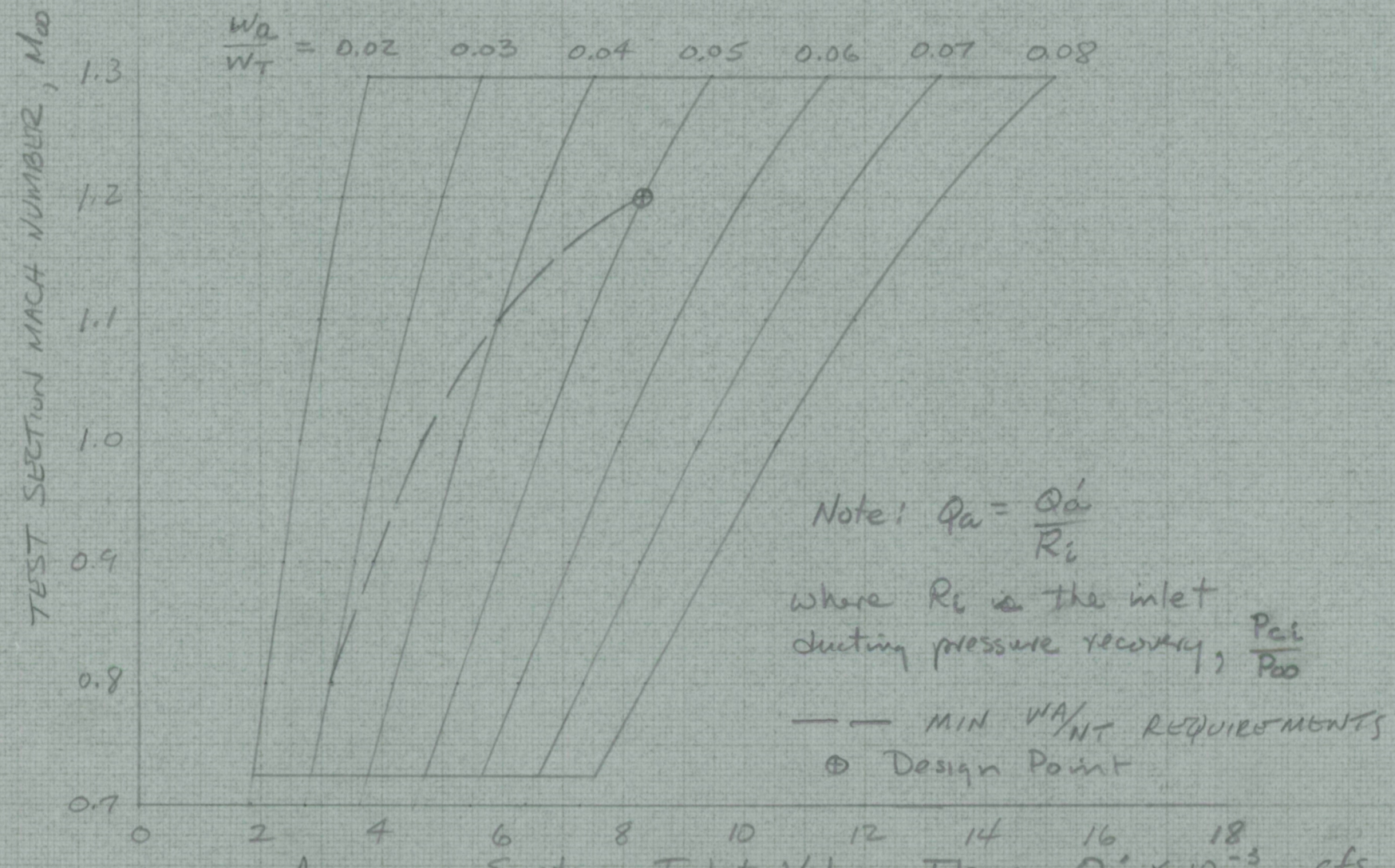

Fig 21. Auxiliary System Volume Flow Requirements for FREON; $T_t = 125°F$.

5/29/73
FMJ.

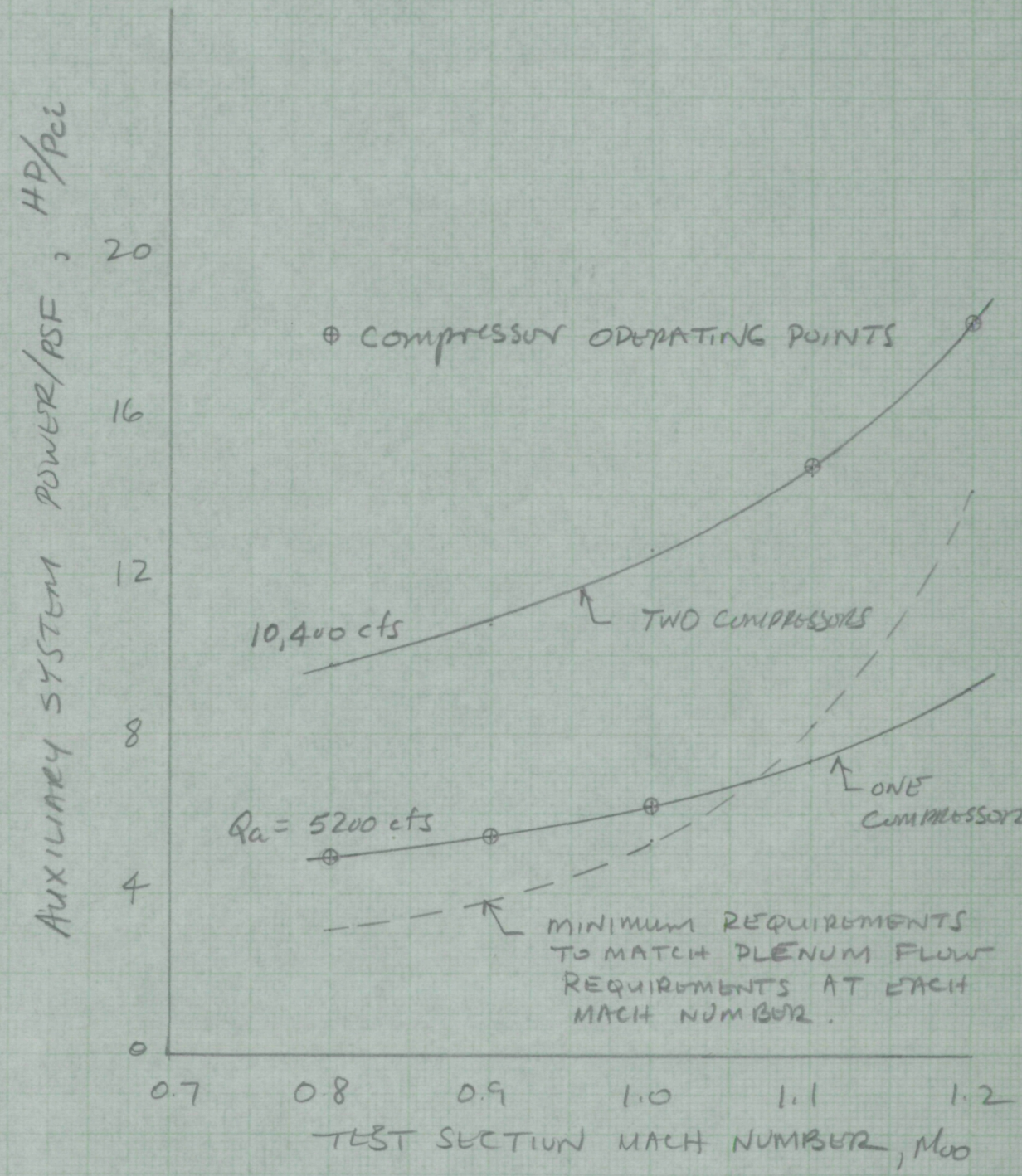

FIG. 22 Auxiliary System Power/PSF with Freon as a Test Medium.

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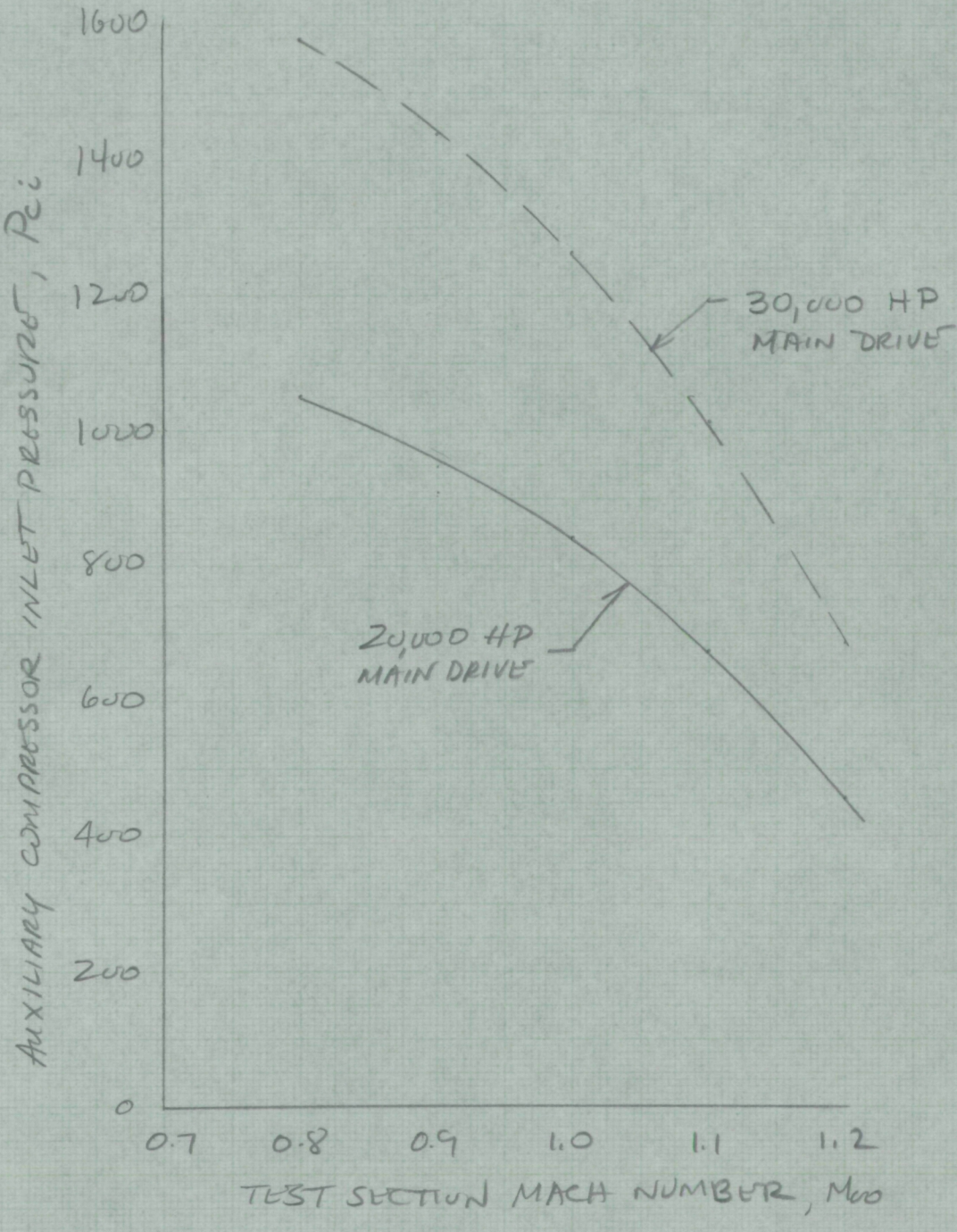

FIG 23 Auxiliary System Compressor Inlet pressure for a 20,000 and 30,000 HP MAIN DRIVE, and WITH FREON as a test medium.

FMJ
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revised 6/3/73

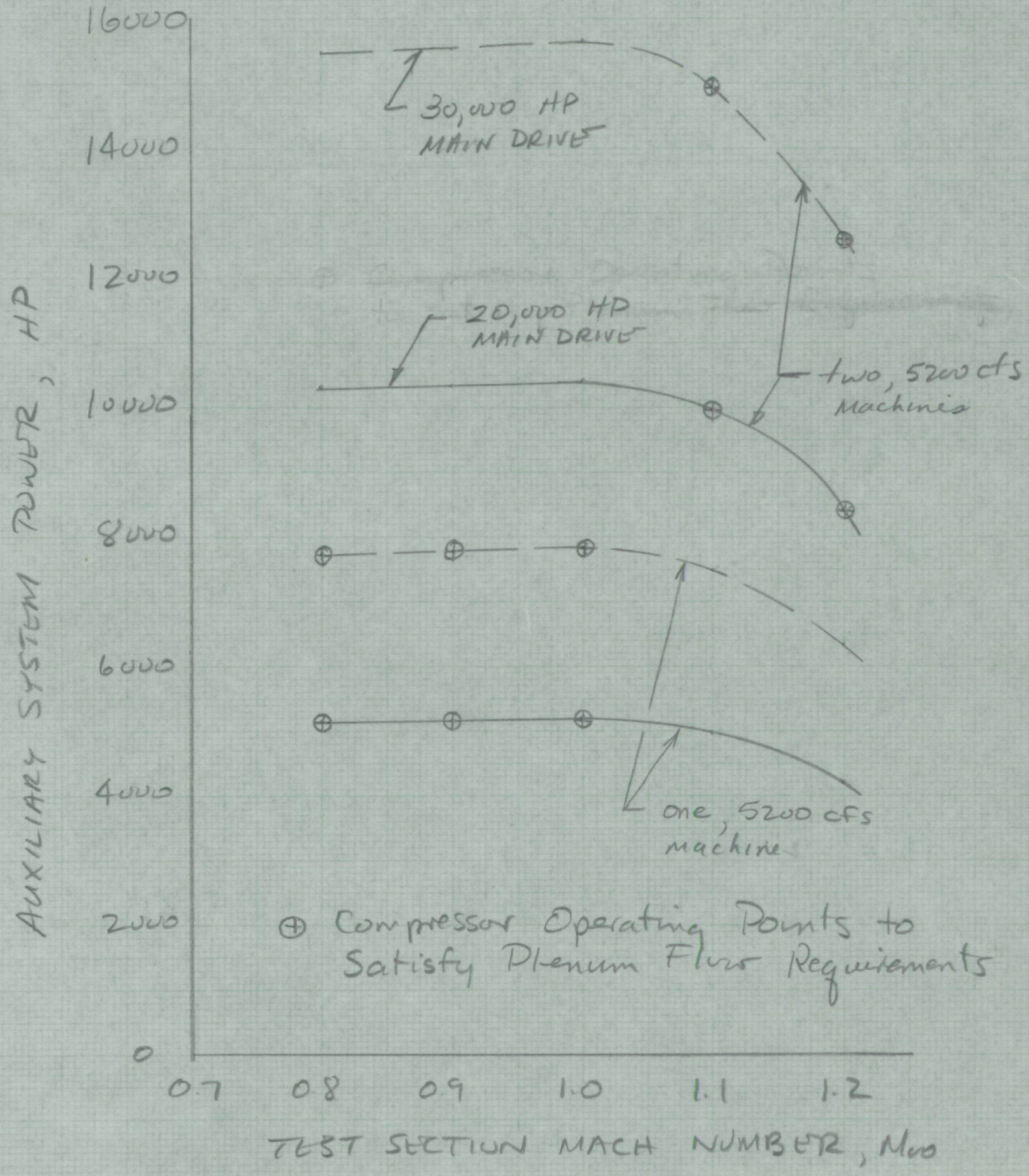


Fig 24. Auxiliary System Power Requirements for Freon with a 20,000 and 30,000 H.P. MAIN DRIVE.

FMJ.
5/30/73.
revised
6/13/73

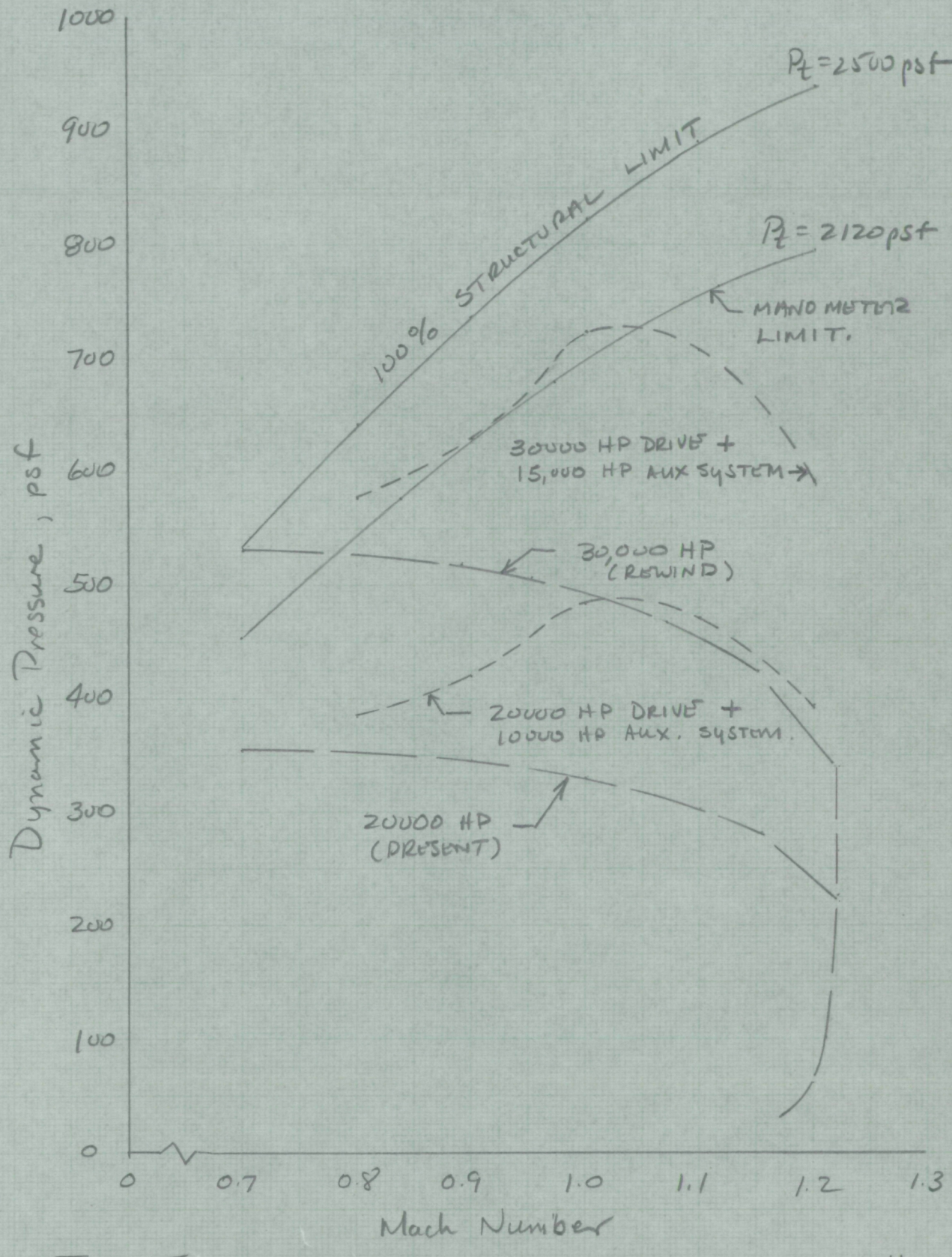


Fig 25 ESTIMATED TDT Performance with Freon for the Addition of 10,000 and 15,000 HP auxiliary compressor systems.

FMJ
6/4/73

APPENDIX C

CIRCUIT PRESSURE LOSSES

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. 1 OF 1

DATE 5/12/73

COMPUTATIONS FOR q & P_t at NORMAL RATED MAXIMUM POWER

BY [signature] CHKD

The following data obtained from either the 18 mm line or H = 2120 psf line as read or calculated from Fig 1 of the LWP-799.

Mach	P_t (AIR)	q (AIR)	P (AIR)	P_t (FREON)	q (FREON)	P (freon)
0.1	2120	15	2105	2120	13	2111
0.2	2120	58	2062	2120	48	2071
0.3	2120	125	1992	2120	105	2018
0.4	2120	213	1899	2120	180	1939
0.5	1900/1030	280/152	1602/868	2120	260	1840
0.6	755	150	592	2120	350	1728
0.7	590	146	425	1650	350	1254
0.8	480	141	315	1370	348	960
0.9	400	133	236	1165	340	744
1.0	335	124	177	995	325	575
1.1	285	113	133	850	300	440
1.2	240	100	99	640	240	293

Notes: P_t is total pressure, psfa
q is dynamic pressure, psfa
P is static pressure, psfa

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY.

SHEET NO. 1 OF 1

DATE 5/15/73

COMPUTATIONS FOR MAIN DRIVE HP/ft² BY J M Jackson CHKD

The desired result is to obtain a comparision of the TDT HP/ft² at standard sea level conditions with that of other large scale wind tunnels. From Goethert book "Transonic Wind Tunnel Testing" and from data supplied by George Stokes of NASA the following HP/ft² were obtained.

Mach	AEDC 16ft M/N suction	AEDC 16 ft MAX suction	NASA 16ft 12% open	NASA 8ft 4% open
0.2	–	–	0	
0.4	–	–	25	
0.6	415	–	85	100
0.8	455	375	145	180
1.0	495	425	245	260
1.2	545	425	325 @ 1.08	450
1.4	630	505		
1.6	800	660		

For the TDT tunnel, the performance at 20,000 HP and T_t = 120°F must be scaled to sea level standard conditions. For a test section area of 241.08 and a Temperature scaling factor of 0.9468 we obtain:

Mach	Horsepower	HP/ft² at rated performance	P_t; FREON normal perf.	HP/ft² FREON scaled cond.	P_t, AIR normal perf.	HP/ft² AIR scaled cond.
0.4	9500 - Freon 14000 - AIR	39/58	2120	37	2120	55
0.6	20,000	83.0	2120	79	755	220
0.8	20,000	↓	1370	121	490	347
1.0	20,000		995	167	335	500
1.2	20,000		640	260	240	694

Note: standard condition: P_{t_0} = 2120 psf, T_{t_0} = 60°F.

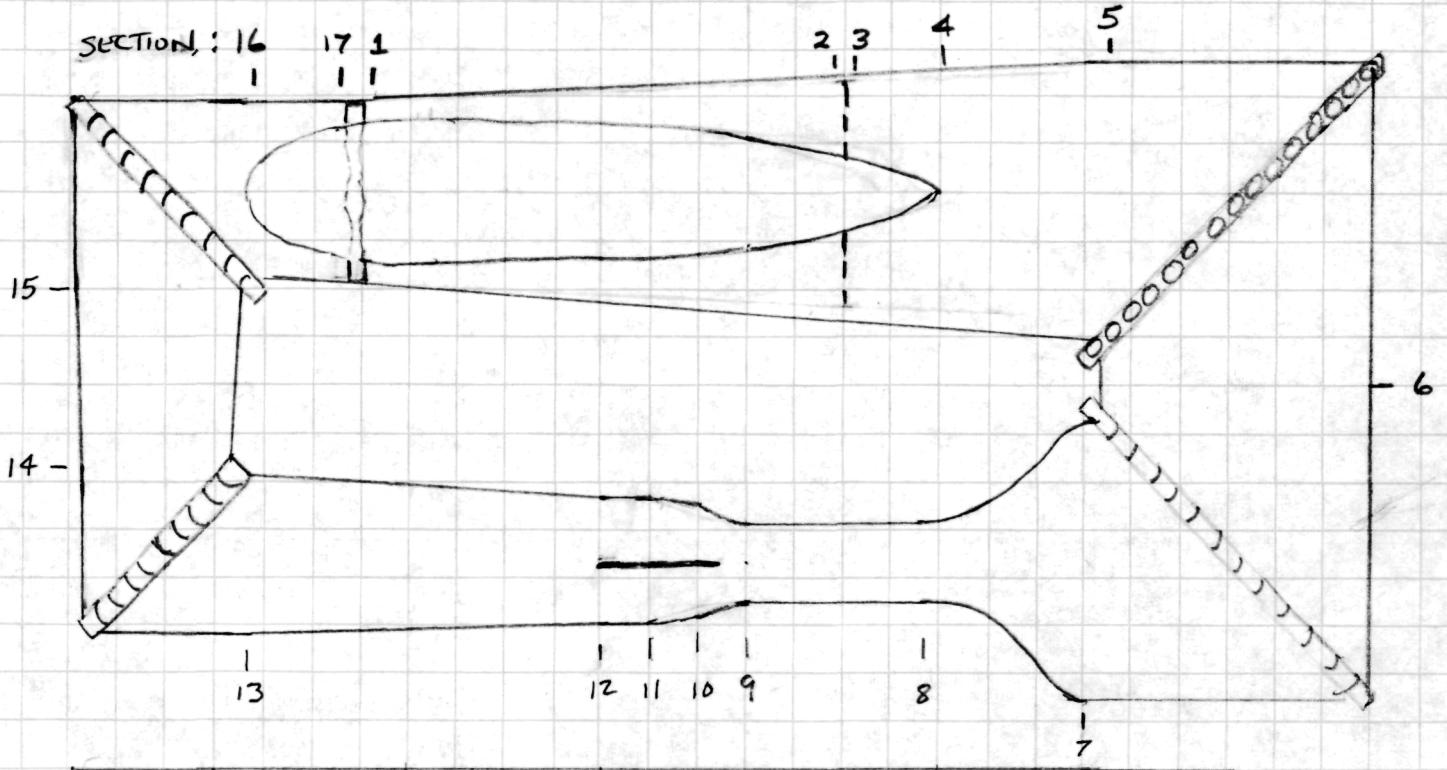
SVERDRUP & PARCEL

JOB LANGLEY TDT PERFORMANCE STUDY SHEET NO. 1 OF 9

COMPUTATIONS FOR TUNNEL LOSSES DATE 10/17/72

BY JJ Jackson CHKD

A. TUNNEL LAYOUT FOR LOSS STUDY.



SECTION	TUN. STA. (ft)	D_{SHELL} (ft)	D_{NAC} (ft)	Area (ft^2)	D_{EQ} (ft)	D_{HYD} (ft)
1	191 b	35.00	26.88	394.64	22.42	8.12
2	75 b	45.23	15.35	1421.67	42.54	29.88
3	75 b	45.23	15.35	1421.67	42.54	29 88
4	50 b	48.05	0	1813.33	48.05	48.05
5	0 b	53.75		2269.06	53.75	53.75
6	50 c	53.75		2269 06	53.75	53.75
7	0	53.75		2269.06	53.75	53.75
8	45			241.08	17.52	16.50
9	80			245.23	17.67	16.63
10	96			292.04	19.28	11.70
11	109	19.75		306.35	19.75	12.07
12	129	20.17		319.59	20.17	20.17
13	214	29.76		695.81	29.76	29.76
14	33 c	29.76		695.81	29.76	29.76
15	66 c	33.48		880.39	33.48	33.48
16	215 b	33.48	0	880.39	33.48	33.48
17	194 b	35.00	25.60	447.39	23.87	9.40

b: backleg
c: crossleg

B. LOSS ELEMENT CHARACTERISTICS.

ELEMENT	Sections	Component	Type Loss	L (ft)	2Θ(deg)	$D_{HS\,AVG}$(ft)	
1	1-2	Backleg Diffuser	Expansion	116	9.90	19.00	
2	2-3	Screen	Screen				
3	3-4	Backleg Diffuser	Expansion	25	12.56	38.97	
4	4-5	Backleg Diffuser	Expansion	50	6.54	50.90	
5	5-6	Corner / Cooler	Corner				
6	6-7	Corner "D"	Corner				
7	7-8	Contraction	Contraction	45		35.12	
8	8-9	Test Section	Test Section	35	~0	16.56	
9	9-10	Transition	Expansion	16	5.40	14.17	←
10	10-11	Transition	Expansion	13	6.00	11.89	
11	11-12	Transition	Expansion	20	0.63	16.12	
12	12-13	1st. Diffuser	Expansion	85	6.46	24.97	
13	13-14	Corner "A"	Corner				
14	14-15	2nd Diffuser	Expansion	30	7.10	31.62	
15	15-16	Corner "B"	Corner				
16	16-17	Fan Nacelle Tip	Contraction	21		21.44	
17	17	Fan					

C. LOSS CALCULATION EQUATIONS;

REF's. (1) PINDZOLA M. "Supersonic Wind Tunnel Design & Performance" AEDC-TM-58-3, 1958

(2) Pope A. "Wind Tunnel Testing, 1958

(3) Gunn J. "Ducting Losses", Internal ARO/PWT Document, 1968

C. cont.

The total pressure loss coefficient, $K_T = \Delta P_t / q$, for each element may be made up of either a fixed loss (ie dependent upon geometry or type of element) or a frictional loss or both.

FOR EXPANSIONS:

$$K_T = K_d \left[1 - \frac{A_{inlet}}{A_{exit}}\right]^2 + \lambda \frac{L}{D_{H,\,AVG.}}^{*}$$

where $K_d = f(2\theta)$ and

λ = skin friction coefficient = $f(R_N)$

FOR CONTRACTIONS:

$$K_T = 0.32\,\lambda \frac{L}{D_{H,\,AVG}}$$

FOR STRAIGHT DUCTS:

$$K_T = \lambda\, L / D_{H,AVG}$$

FOR CORNERS: K_T = cont = f (design)

FOR screen: K_T = cont = f (porosity)

* Note: $D_{H,AVG}$ = AVG. HYDRALIC DIAM = $\frac{4 \cdot \text{Area}}{\text{Perimeter}}$.

D. LOSS CALCULATION ASSUMPTIONS.

(1) Test Section Properties: $M_0 = 0.70$, $P_{t_0} \cong 500$ psf, $T_t = 120°F$

(2) FOR 16.5 mw cond ΔT_t cooler = 40° ∴

$T_{t_1}, T_{t_2} \cdots T_{t_5} = 620°R$

$T_{t_6}, T_{t_7} \cdots T_{t_{17}} = 580°R$

(3) P_{t_1} (fan exit) = 510 psf.

(4) Strut thickness is neglected for Area calculations at sections 10 & 11.

(5) Vanes neglected in Area calculation at sect. 16.

(6) For screen, POROSITY = 53% & $K_T = 1.60$

(7) FOR CORNER "C" (COOLER); $K_T = 1.00$

(8) FOR CORNER A, B, & D; $K_T = 0.22$

(9) FOR SLOTTED Test Section; $\lambda_{S.TS} = 4\,\lambda_{\text{smooth T.S.}}$

(10) FOR STRUT; $C_D = 1.0$ and $K_{T\,\text{STRUT}} = 0.015$

(11) λ (friction factor) for element = $f(R_{n\,AVG})$

where $R_{n\,AVG} = \dfrac{R_{n\,\text{inlet}} + R_{n\,\text{exit}}}{2}$

(12) Adiabatic conditions

E. STREAM PROPERTIES.

CIRCUIT WEIGHT FLOW:

$$W = \left(P/P_t \dot{m}\right) \frac{P_t A}{\sqrt{T_t}}$$

where $P/P_t \dot{m} = f(M)$ from OAL 50 (1952)

for $M_0 = 0.70$ $P/P_t \dot{m} = 0.485$

$$W = 0.485 \frac{500\,(241.08)}{\sqrt{580}} = 2427.5 \text{ \#/sec.}$$

TOTAL VOLUME FLOW

$$Q_x = \left(P/P_t \dot{m}\right) \frac{AR}{g} \sqrt{T_t}$$

for sta 8. 1716

$$Q_8 = 0.485 \frac{241.08 \times 53.35 \times \sqrt{580}}{32.174} = 150{,}200 \text{ cfs.}$$

FOR each section:

$$M_x = f\left(P/P_t \dot{m}\right) = f\left(\frac{W\sqrt{T_t}}{P_t A}\right)_x$$

and $q_x = f(M_x)$

$$R_{n_x} = \frac{\rho V D_H}{\mu}$$

FOR SECTION STREAM PROPERTIES SEE FIGS 1a & 1b.

F. SUMMARY OF LOSS CALCULATIONS.

ELEMENT	FIXED LOSS COEFF.	FRICTION LOSS COEFF.	TOTAL LOSS COEFF	q	ΔP_t	K_{ox}*	% LOSS
1	0.0992	0.0573	0.1565	40.53	6.35	0.05315	18.2
2	1.60	—	1.60	2.99	4.78	0.04051	13.8
3	0.0110	0.0059	0.0169	3.02	0.05	0.00043	0.2
4	0.0052	0.0090	0.0142	1.85	0.03	0.00026	0.1
5	1.00	—	1.00	1.18	1.18	0.01010	3.4
6	0.220	—	0.220	1.11	0.24	0.00193	0.7
7		0.0033	0.0033	124.44	0.42	0.00337	1.2
8	~0	0.0660	0.0660	124.44	8.21	0.06598	22.5
9	0.0210	0.0092	0.0302	122.24	3.69	0.03015	10.3
10	0.0012	0.0094	0.0106	78.47	0.83	0.00683	2.3
11	~0	0.0100	0.0100	70.27	0.71	0.00586	2.0
12	0.0380	0.0276	0.0656	63.87	4.19	0.03461	11.8
13	0.220	—	0.220	12.44	2.74	0.02283	7.8
14	0.0057	0.0080	0.0137	12.51	0.17	0.00142	0.5
15	0.220	—	0.220	7.76	1.70	0.01425	4.9
16		0.0028	0.0028	31.35	0.09	0.00076	0.3

* K_{ox} = LOSS COEFFICIENT RELATED TO JEST SECTION q

so that $E.R. = \frac{1}{\Sigma K_{ox}}$

for $M_8 = 0.70$, $P_{to} = 500$

$\Sigma K_{ox} = 0.29279$ and $E.R. = 3.415$

See Figures 2a and 2b, for % LOSS SUMMARY.

G. Conclusions

(1) The data indicate that there are several tunnel components with high losses. The highest loss is indicated in the test section, however, the friction coefficient was assumed for this component.

(2) The Test-section and Diffuser only account for about 49% of the tunnel losses. This would indicate that modification to other tunnel components might be considered, to improve tunnel performance.

(3) These data indicate an energy ratio (ER) of 3.415 @ $M = 0.70$. This is based on $ER = 1/\Sigma K_{ox}$. Utilizing

$$E.R. = \frac{1}{2} \rho_o A_o V_o^3 / \text{power input} \times \eta$$

G. cont.

and assuming $\eta = 0.90$, E.R. = 2.12

This discrepancy in E.R. indicates that

(a) either the losses are higher than calculated.

or

(b) the efficiency is lower than assumed.

(4) According to Del Taylor a good diffuser should have an Area ratio of about 4.0

Depending upon whether we select Sta 80 or Sta 129 for our diffuser entrance we have an area ratio of either 2.8 or 2.2 thus for the installed diffuser angles the diffuser is either 68 or 93 ft too short. This is probably why NASA personnel have frequently made reference to diffuser loss measurements.

G. cont.

(5) The data indicate a fan pressure rise of 35.4 psf. This corresponds to a pressure ratio of 1.075. The fan inlet volume flow is 158,200 cfs at the assumed conditions.

(6) A pressure ratio of 1.075 is not to bad for $M = 0.70$. Poor tunnel performance might then be a result of poor fan performance, ie. low fan efficiency. An attempt should be made to measure the fan efficiency.

(7) These data provide information for the evaluation of circuit loss measurements and provide indication of desirable locations for pressure orifices for the circuit loss study.

FIG 1a. STREAM PROPERTIES. ~ TDT.

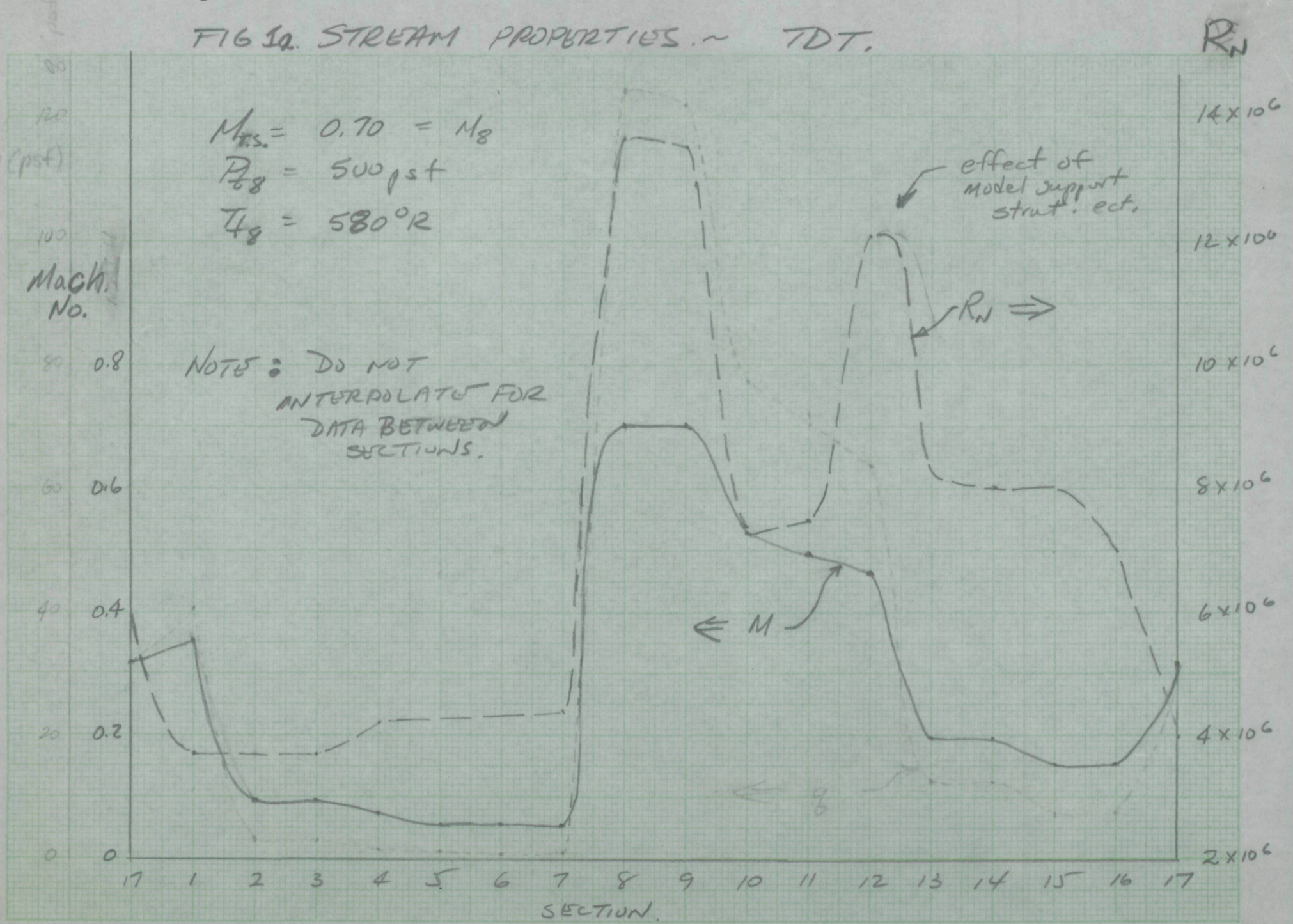


Fig 16 ~ ratio of local total pressure to stilling chamber pressure

KEUFFEL & ESSER CO. 46 1320 10 X 10 TO ⅛ INCH

FIG 2a % LOSS for each element, LANGLEY TDT

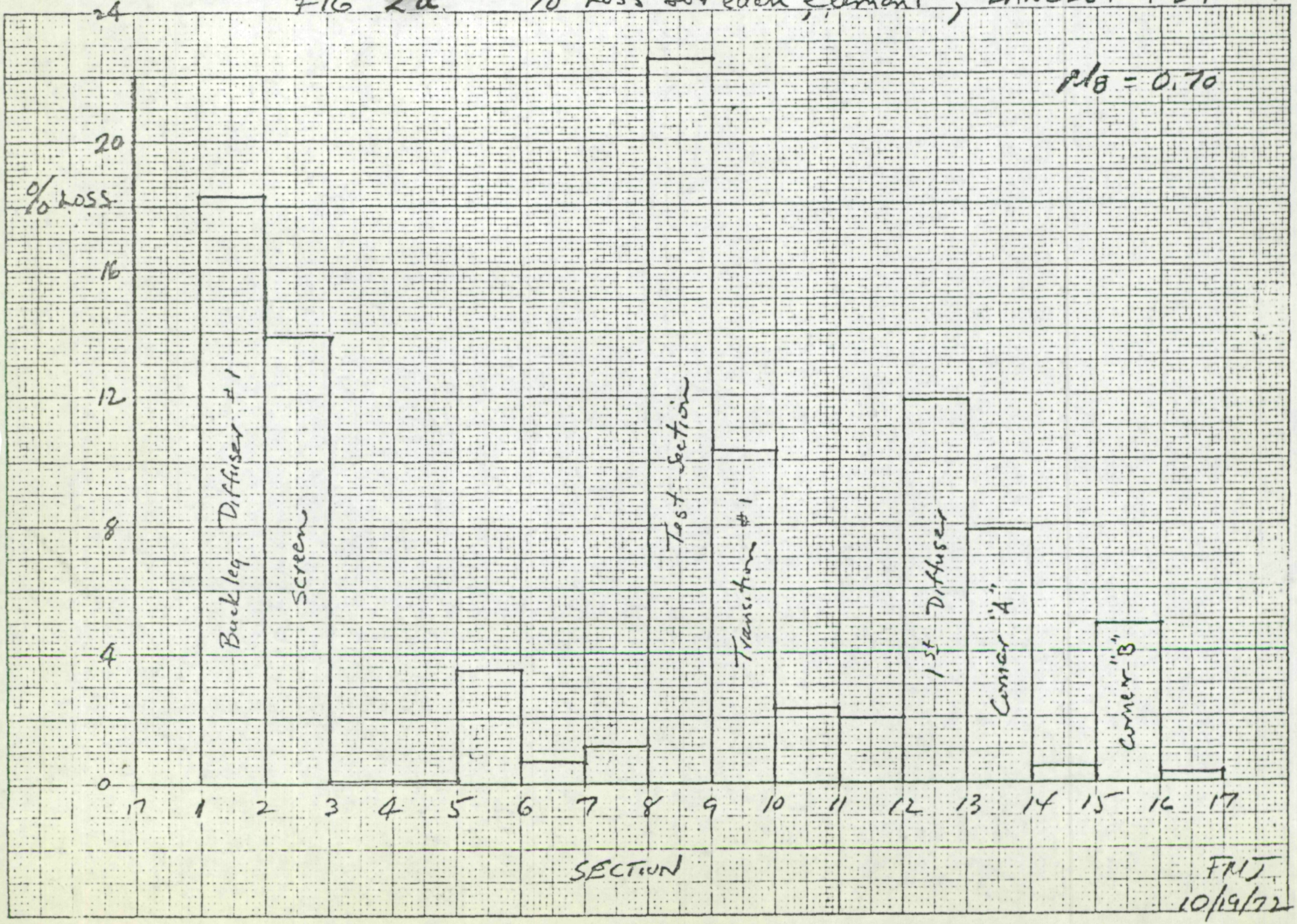


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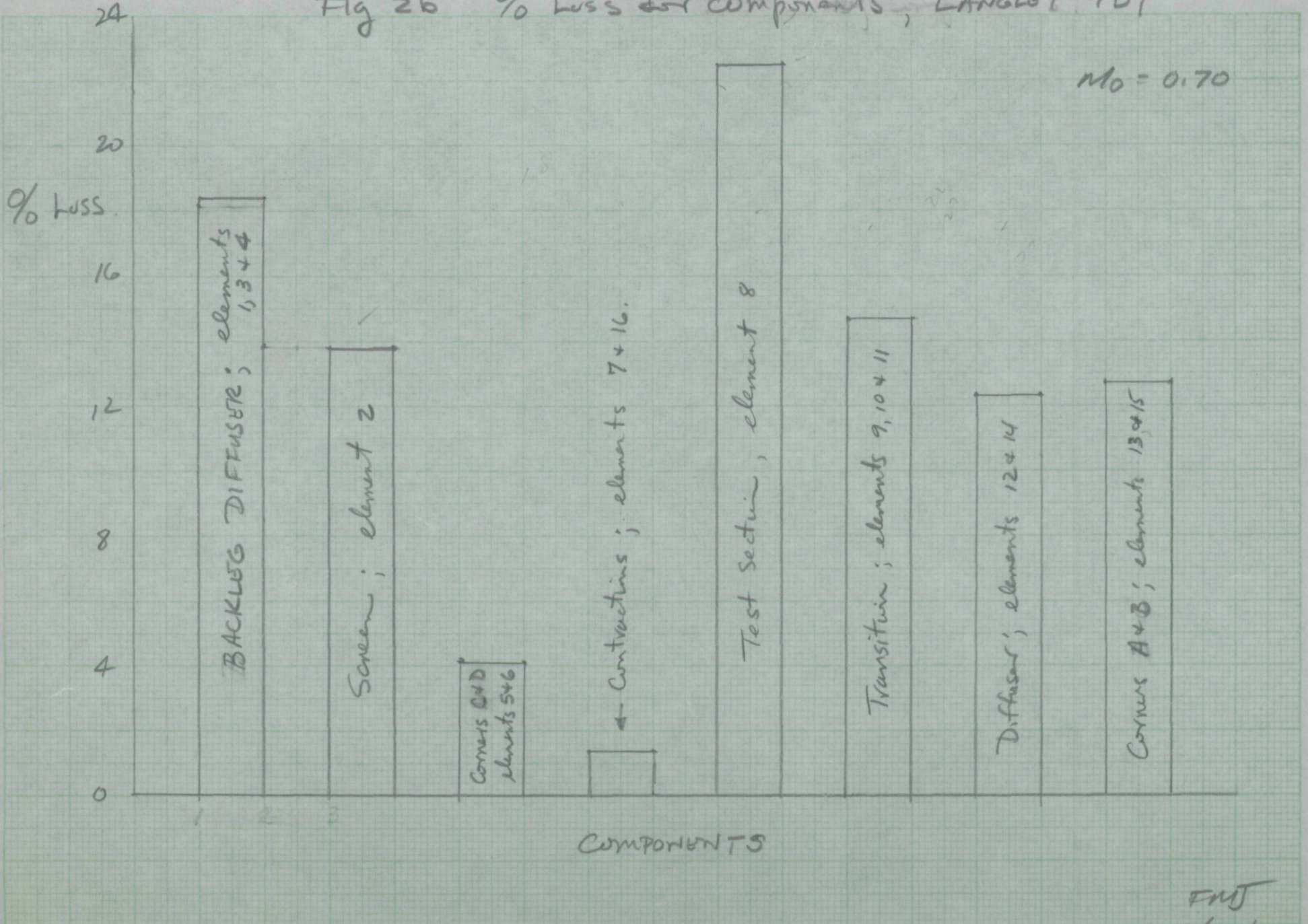
Fig 26 % Loss for components, LANGLEY TDT

$M_0 = 0.70$



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10/19/72

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 1 OF 14

COMPUTATIONS FOR TUNNEL CIRCUIT LOSSES DATE 5/9/73

BY CHKD

I. Review of early work (10/17/72)

This work was generated to determine if cleanup of any of the tunnel components could significantly increase tunnel performance. This work indicated that there were several "high" loss components in the circuit. As a result of this work it was recommended that a pressure loss test should be conducted for the TDT prior to making firm recommendations for tunnel improvements. For this reason the calculation of circuit losses was limited to those for $M = 0.70$.

II Need for Further Work.

When it became apparent that the test program probably would not be conducted during the contract period, the need for additional circuit loss calculations arose. These results were needed for two purposes:

(1) to obtain additional information, particularly in the 0.8 to 1.2 Mach range, which hopefully would lead to recommendations for tunnel "cleanup".

(2) to obtain data to support the evaluation of utilization of an auxiliary compressor system for plenum flow removal.

The decision was made to compute circuit losses at the test conditions requested for the performance test. These conditions and the procedures used for obtaining the fan exit conditions are given in the next section.

III Initial Conditions

As indicated in the early work (10/17/72) station 1 is selected just downstream of the fan. The fan exit temperature is a function of inlet temperature, compression ratio, compressor efficiency and the test medium: ie.

$$T_{te} = \frac{T_{ti}\left(\lambda_c^{\frac{\gamma-1}{\gamma}} - 1.0\right)}{\eta} + T_{ti}$$

If λ_c is considered to be determined by the 11/17/72 work (Auxiliary System Compression Ratio), then λ_c varies with Mach number as shown in fig 1.

Assuming for max power operation that $T_{ti} = T_{t\infty} = 585°R$ and $\eta = 0.75$, we obtain for $\gamma = 1.13$ for Freon and 1.40 for Air:

M	Freon		Air	
	λ_c	T_{te}	λ_c	T_{te}
0.4	1.018	587	1.022	590
0.7	1.050	590	1.062	599
0.9	1.080	592	1.110	609
1.0	1.096	593	1.120	611
1.1	1.129	596	1.159	619
1.2	1.200	602	1.250	636

Note: For loss calculations T_{te} to be rounded off to nearest 100.

III cont.

The loss calculations will be made at the total pressures requested for the TDT performance test. These are near maximum power, therefore assume $T_{t_0} = 585°F$.

now $$W/P_t = \dot{m}\frac{P}{P_t}\frac{A}{\sqrt{T_{t_0}}}$$

where $A = 241.1\ ft^2$ & $\dot{m}P/P_t = f(\text{Mach, medium})$

To obtain fan exit pressure, P_{te}, it was assumed that from 33% ($M \leq 1.0$) to 25% ($M > 1.0$) of the losses occured between the fan exit & the stilling chamber. The fan exit temperature is obtained from previous work.

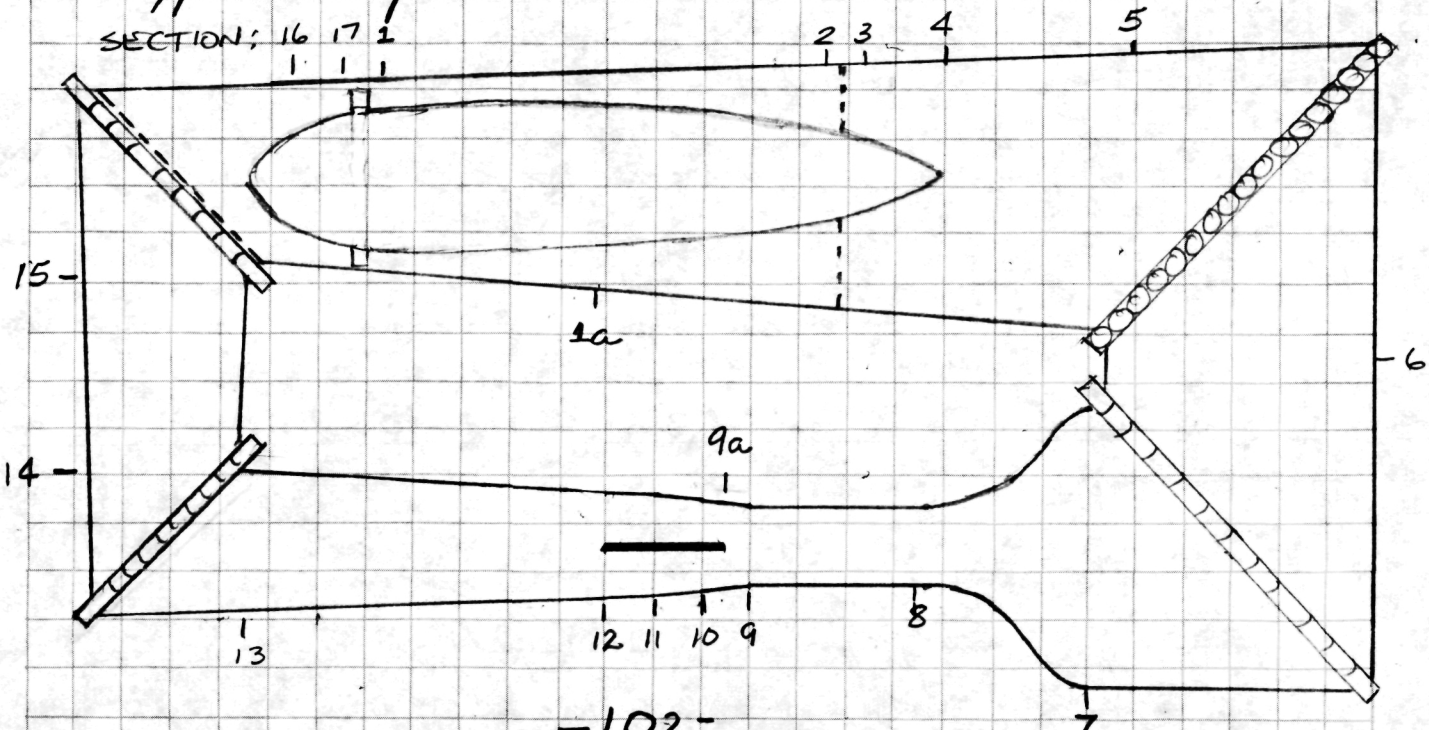
Medium	Mach	P_t	$\dot{m}P/P_t$	W/P_t	W, #/sec	~P_{te}	T_{te}
AIR	0.4	2000	0.33442	3.3335	6667.0	2015	590
AIR	0.7	750	0.48592	4.8438	3632.9	765	600
AIR	0.9	500	0.52710	5.2543	2627.2	515	610
AIR	1.0	400	0.53177	5.3008	2120.3	415	610
AIR	1.1	350	0.52759	5.2592	1840.7	365	620
AIR	1.2	300	0.51606	5.1442	1543.3	315	640
Freon	0.4	2000	0.60825	6.0632	12126	2010	590
Freon	0.7	2000	0.89614	8.9330	17866	2030	590
Freon	0.9	1300	0.97840	9.7529	12679	1330	590
Freon	1.0	1100	0.98804	9.8490	10834	1130	590
Freon	1.1	950	0.97916	9.7605	9272.5	980	600
Freon	1.2	700	0.95427	9.5124	6658.7	735	600

Note: T_{te} rounded off to nearest 10°. After the cooler it is assumed that $T_t = 585°F$.

IV TUNNEL LAYOUT.

The locations of tunnel stations for the circuit loss calculations were slightly modified to coincide with the measuring stations as planned for the performance test. In addition the Langley TDT nomenclature is utilized. Only three significant changes were made, these are: (1) the deletion of section 1a at station ℄ 132, (2) the inclusion of section 9a, which is a function of Mach number, to account for shock and flap losses and (3) the inclusion of a safety screen which is installed at corner B. Information on TDT screens is given on page 6.

The tunnel layout and the characteristics of loss elements are given below. In some cases physical dimensions of some components were modified according to the latest information supplied by Frank Abbott of NASA.



SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 5 OF 14

LOSS ELEMENT CHARACTERISTICS DATE 4/29/73; 5/9/73

COMPUTATIONS FOR (CIRCUIT LOSS CALCULATIONS) BY [signature] CHKD

IV cont.

Section	Station	Type Loss	Area, ft²	Deq, ft	2θ, °	K_T (FIXED	D_H, ft	L, ft	Sect. D_H, AVG
1	E191	Expansion	394.6	22.41	7.6	0.0264	8.12	59	11.49
1a	E132	Expansion	718.0	30.23	12.3	0.0564	14.86	55	22.13
2	E77	Screen	1394	42.13	—	1.60	29.40	—	—
3	E75	Expansion	1422	42.55	12.6	0.0116	29.88	25	38.96
4	E50	Expansion	1813	48.05	6.5	0.0052	48.05	50	50.90
5	E0	Corner + Cooler	2269	53.75	—	1.00	53.75	—	—
6	S5	Corner	2214	53.09	—	0.22	—	—	—
7	W0	Contraction	2214	53.09	—	—	53.09	44	34.80
8	W44	Test Section	241.1	17.52	—	—	16.50	36	16.56
9	W80	Expansion	245.2	17.67	5.8	0.0034	16.63	16	13.92
9a	—	Shock + Flap Loss	f(MACH)	—	—	f(MACH)	—	—	—
10	W96	Expansion	279.0	19.28 / 13.32	1.1	0.0003	11.20	13	11.29
11	W109	Expansion	289.0	13.56	2.0	0.0020	11.38	20	15.78
12	W129	Expansion	319.6	20.17 / 14.26	6.5	0.0380	20.17	85	24.97
13	W214	Corner	695.8	29.76	—	0.22	29.76	—	—
14	N0	Expansion	695.8	29.76	6.5	0.0057	29.76	33	31.62
15	N33	Corner + Screen	880.4	33.48	—	0.60	33.48	—	—
16	E212.5	Contraction	795.0	31.82	—	—	23.28	18.5	16.34
17	E194	Fan (Rise)	447.4	23.87	—	—	9.40	—	—

NOTES: (1) REFER TO 10/17/72 work for equations, ect.
(2) ON station, E, W, ect. refers to East, West. ect.
(3) Two sets of dimensions at stas, 10 and 12 are required to consider effect of strut upon corresponding elements.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 6 OF 14

COMPUTATIONS FOR LOSSES FOR SCREENS (TUNNEL CIRCUIT LOSSES) DATE 4/26/73 & 5/9/73

BY CHKD

IV cont.

(A) FOR the screen downstream of the fan the wire is 0.0625 in diam with a 0.25 x 0.25 mesh.

porosity, $\beta = \left(1 - \frac{.0625}{.250}\right)^2 = .562$

and $K_T = \frac{\Delta P}{q} \cong \left(\frac{1-\beta}{\beta^2}\right) \cong 1.4$

Note: a TDT drawing shows $\beta = 53\%$ for $K_T = 1.60$

Abbott says screen designed for $K_T \cong 1.50$ and that screen galvanized such that porosity is less than one would calculate. ∴ use $K_T = 1.60$

(B) For the safety screen we have two screens on top of one another.

Screen 1 has 0.031 wire with 0.25 x 0.25 mesh

Screen 2 has 0.125 wire with 2.0 x 4.0 mesh

so that $\beta_1 = 0.767$ and $K_{T_1} = 0.32$

and $\beta_2 = 0.918$ and $K_{T_2} = 0.08$

It is reasonable to assume that screen 2 would tend to reduce the porosity of screen 1 Abbott also says that at the bottom of the screen there is a 6" wide solid strip and that a 1" wide strip is around the edge.

For about a $\beta \cong 0.75$ $K_T = 0.40$, Since this screen is attached to the turning vanes these losses will be also be included for a total corner "B" loss coeff, $K_T = 0.60$.

I LOSS CALCULATION EQUATIONS.

The equations and procedures utilized in the loss calculations are adequately presented in the early work (10/17/72)

Five additional references were utilized as follows:

(1) Goethert, B.H, "Transonic Wind Tunnel Testing, Agardograph # 49, 1961

(2) Wyatt, D. "Analysis of Errors Introduced by Several Methods of Weighing Non-Uniform Duct Flows", NACA TN 3400, 1955.

(3) Henry, J., Wood, C. and Wilbur, S. "Summary of Subsonic-Diffuser Data, NACA RM L56F05, 1956.

(4) Wood, C. and Henry J. "Effects of Shock-Boundary-Layer Interaction on the Performance of a Long and Short Subsonic Annular Diffuser," NACA RM L58A31, 1958.

(5) Staff, Langley Field "LWP-799", 1969

VI ASSUMPTIONS,

A. Review of Previous Assumptions

Following the 10/17/72 work F. Abbott made data available which gave an indication of the fan compression ratio. These data (see fig 1 and 10/17/72 work) indicated that the loss calculations at at M=0.7 were too high. It has been decided that the discrepancy was in the assumed loss coefficients for the test section and strut. For these

II cont.

Initial loss calculations: (1) the strut loss which is somewhat intangible, is neglected, however, the effect of the strut on duct area and duct friction losses is considered. (2) the skin friction coefficient for the test section is assumed as $\lambda_{STS} = 2\,\lambda_{SMOOTH\ TS}$.

B. Additional Assumptions.

For the initial loss calculations, the following additional assumptions are also made:

(3) The loss coefficient for Corner B and the screen at corner B are combined. (See page 6 for screen data; $K_T = 0.60$.

(4) The loss coefficients for the contractions (elements 7 & 16) are assumed as: $K_T = 0.0030$ for Air & $K_T = 0.0024$ for Freon

(5) At $M > 0.7$ the diffuser flow separates such that the fixed loss coefficients for the 1st diffuser (sta 80-214) are doubled.

(6) At supersonic Mach numbers a normal shock occurs between Sta 80 & 96. A theoretical one-dimensional shock loss is assumed; however, because of the utilization of slap suction the shock Mach no. is higher than M_∞. (See pages 9 & 10)

(7) For $M > 0.8$, the introduction of low energy air through the flaps constitutes a high loss. (See page 11 for loss coefficients)

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. 9 OF 14

DATE 4/28/73 + 5/9/73

COMPUTATIONS FOR SHOCK LOSS AT SUPERSONIC OPERATION. BY FM Jackson CHKD

VI cont.

Assume for operation at $M \geq 1.0$ flow expands to a higher Mach number between Stas 80 and 96. This is necessary to pump flow with flaps.

(1) What is area at shock? This is dependent upon test section & shock Mach number, & Medium

Assume for $M_{STA\,80} = 1.0$; $M_{SHOCK} = 1.10$

$$A_{SHOCK_{AIR}} = A_{STA\,80} \cdot \left(\frac{A^*}{A}\right)_{M STA 80} \cdot \left(\frac{A}{A^*}\right)_{M SHOCK}$$

$$A_{SHOCK_{AIR}} = 245 \cdot \frac{1.008}{1.00} = 247 \text{ ft}^2$$

Assume for $M_{STA\,80} = 1.2$, $M_{SHOCK} = 1.40$

$$A_{SHOCK_{AIR}} = 245 \cdot \frac{1.115}{1.03} = 265 \text{ ft}^2$$

(2) What is loss coefficient? This is dependent upon conditions upstream of the shock. ie.

for $K_T = \frac{\Delta P_t}{q}$, $q = \frac{\gamma}{2} P_1 M_1^2$

1 : upstream of shock

and $\Delta P_t = P_{t_1}\left[1 - \left(\frac{P_{t_2}}{P_{t_1}}\right)_{f(M_{SHOCK})}\right]$

For which: $K_T = \frac{\left[1 - \left(\frac{P_{t_2}}{P_{t_1}}\right)\right]}{q/P_{t_1}}$

M_{SHOCK}	K_T (FROM [illegible])
1.1	.0029
1.2	.0073
1.4	.0970

VII cont.

Now $\frac{q}{P_t} = \frac{\gamma}{2}\left(\frac{P}{P_t}\right) M^2$

and $\frac{P_{t_2}}{P_{t_1}} = \left[\frac{(\gamma+1) M_1^2}{(\gamma-1) M_1^2 + 2.0}\right]^{\frac{\gamma}{\gamma-1}} \left[\frac{(\gamma+1)}{2\gamma M_1^2 - (\gamma-1)}\right]^{\frac{1}{\gamma-1}}$

for $\gamma = 1.4$ for Air and 1.13 for Freon

we have for loss coefficients:

M_{SHOCK}	K_T (AIR)	K_T (FREON)
1.10	.0028	.0030
1.20	.0173	.0209
1.30	.0482	.0593
1.40	.0970	.1215

for Freon:

$$\frac{A^*}{A} = \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} M \left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{(\gamma+1)}{2(\gamma-1)}}$$

for $M_{80} = 1.0$; $M_{SHOCK} = 1.10$ $A_{SHOCK} = 245 \frac{1.009}{1.0} = 247\ ft^2$

$M_{80} = 1.1$; $M_{SHOCK} = 1.20$ $A_{SHOCK} = 245 \frac{1.035}{1.009} = 251\ ft^2$

$M_{80} = 1.2$; $M_{SHOCK} = 1.40$ $A_{SHOCK} = 245 \frac{1.134}{1.035} = 270\ ft^2$

also for AIR

$M_{80} = 1.1$; $M_{SHOCK} = 1.2$ $A_{SHOCK} = 245 \frac{1.030}{1.008} = 250\ ft^2$

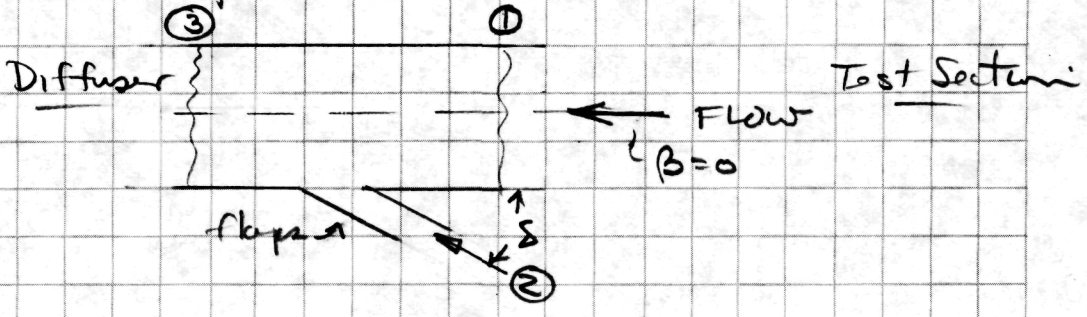
VI cont.

The reentry of plenum flow into the diffuser through the flaps constitutes a converging branch loss which may be calculated (Ref 3 10/17/72 work) from:

$$K_T = \lambda(B) + \left(\frac{G_3}{G_1}\right)^2 - f\left(\beta, \frac{A_1}{A_3}\right) - \left(\frac{G_2}{G_1}\right)^2 \left[f\left(\delta, \frac{A_2}{A_3}\right)\right]$$

where $\frac{G_3}{G_1} = \frac{W_3}{W_1} \cdot \frac{A_1}{A_3}$ and $\frac{G_2}{G_1} = \frac{W_2}{W_1} \cdot \frac{A_1}{A_2}$

and schematically we have:



For $A_1/A_3 = 0.839$ and $B=0$: $\lambda(B) = 0.96$, $f(B) = 1.64$;
Now assuming $\delta = 10°$ and utilizing flap settings as supplied by F Abbott of NASA and estimating the plenum flow removed at each condition (in % of W_1) we obtain:

Mach	flap opening inches	flap Area ft²	W_2 % of W_1	A_2/A_3	$f(\delta)$	G_3/G_1	G_2/G_1	K_T
0.9	0.9	2.4	1.8	0.008	0.016	0.850	1.87	0.0250
1.0	5.3	14.1	3.5	0.048	0.10	0.880	0.63	0.0550
1.1	17.0	45.0	4.2	0.154	0.30	0.880	0.29	0.0780
1.2	17.0	45.0	5.0	0.154	0.30	0.890	0.24	0.0875

VII DISCUSSION OF RESULTS.

An assessment of the pressure loss calculations can be obtained by comparison of the calculated fan compression ratios, i.e, that corresponding to the total circuit pressure loss, with the known fan compression ratios. Unfortunately no formal documentation of the TDT fan compression ratio existed. However some unpublished data (see 11/17/72 work "Aux System Compression ratio") were utilized to define the TDT fan compression ratios for Air and Freon. A comparison of the calculated results with these data is shown in Fig 1. Initial calculations at Mach numbers 1.1 and 1.2 produced pressure ratios which were too low. It was assumed that the shock and slap losses at section 9a were apparently higher than previously assumed. Consequently loss coefficients of 0.090 and 0.045 for Air and 0.045 and 0.0225 for Freon at Mach numbers of 1.2 and 1.1, respectively, were included in addition to those previously assumed for section 9a.

A summary of the pressure loss calculations is presented in Tables 1 and 2. The data included in these tables include:

(1) the pressure loss for each element in psf.
(2) the percent loss attributed to each element

(3) the total pressure loss for the circuit, psf

(4) the pressure ratios for various segments of the circuit, these include (see figs 2 & 3):

(a) $\lambda_C = \frac{P_{t1}}{P_{t17}}$, FAN COMPRESSION RATIO

(b) $\lambda_T = \frac{P_{t8}}{P_{t13}}$, TEST LEG RATIO

(c) $\lambda_B = \frac{P_{t1}}{P_{t8}}$, "BACK LEG" RATIO (includes corners C & D)

(d) $\lambda_R = \frac{P_{t13}}{P_{t17}}$, "RETURN DUCT" RATIO (includes corners A & B)

Note: $\lambda_C = \lambda_T \cdot \lambda_B \cdot \lambda_R$

(5) An approximate Energy Ratio, defined as:

$$ER = \frac{1}{\Sigma K_{ox}} = \frac{q_\infty}{\Sigma \Delta P} = \frac{q_8}{\text{Total } \Delta P}$$

(6) The fan inlet volume flow, cfs.

Note: $Q_{C_i} = Q_{17} = \lambda_C \cdot Q_1 \frac{T_{t17}}{T_{t1}}$

(7) The Air Power, ie. the useful power, mw

(8) An approximate fan efficiency, %. This was based on the calculated air power and the input power as shown in LWP-799, fig 1 but taking into account the brake, rheostat and auxiliary power. (See figs 4 and 5)

The distribution of total pressures around the TDT circuit is shown in Fig 6 and 7. The distribution of Mach number is shown in Fig 8.

The pressure loss of each circuit element in percent of total pressure loss is shown in Figs 9 and 10 for Mach numbers 0.4 and 1.0, respectively. These data that elements 3, 4, 5, 6, 7, 14 and 16 have small losses and hence should not be considered for possible modification. In addition, it appears practical to combine the sections 1 and 1a as the East Leg Diffuser, and to combine sections 9, 10 and 11, the West leg transition for analysis purposes. Accordingly there eight circuit elements lend themselves to consideration for possible modification. The percent loss of these various elements, as a function of Mach number, is presented in Figs 11 to 14. The data in Figs 11 to 14 indicate that for the Mach number range of highest interest (0.8 to 1.2) the components which exhibit the most potential for possible modification are the flap operation, the West Leg Diffuser and the two screens. The highest performance increase can be obtained by replacement of the flap operation by an auxiliary suction system. The margins of improvement will be discussed in other sections.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 1 OF 2

DATE 5/15/73

COMPUTATIONS FOR SUMMARY OF TDT CIRCUIT LOSSES WITH (AIR) BY FH CHKD

TABLE 1

	P_t=2000		P_t=750		P_t=500		P_t=400		P_t=350		P_t=300	
SECTION	M=0.4		M=0.7		M=0.9		M=1.0		M=1.1		M=1.2	
	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%
1	4.8	9.6	4.2	9.7	3.5	7.9	2.9	6.7	2.5	4.9	2.2	3.5
1a	1.6	3.2	1.3	3.1	1.1	2.4	0.9	2.0	0.8	1.5	0.6	1.0
2	8.9	17.8	7.1	16.6	5.7	12.6	4.6	10.7	4.0	7.8	3.4	5.4
3	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0	0
4	0.1	0.1	0	0	0	0	0	0	0	0	0	0
5	2.1	4.2	1.7	3.9	1.4	3.0	1.1	2.6	0.9	1.8	0.8	1.3
6	0.5	1.0	0.4	0.9	0.3	0.7	0.2	0.6	0.2	0.4	0.2	0.3
7	0.6	1.1	0.6	1.3	0.5	1.2	0.4	1.0	0.4	0.8	0.3	0.5
8	5.9	11.8	5.9	13.7	5.6	12.5	5.1	11.9	4.9	9.7	4.6	7.3
9	1.9	3.8	1.9	4.4	2.6	5.8	2.3	5.4	2.2	4.4	2.0	3.2
9a	0	0	0	0	4.7	10.4	9.1	21.3	20.5	40.0	35.6	56.8
10	1.3	2.6	1.2	2.8	1.1	2.4	0.9	2.2	0.9	1.7	0.8	1.3
11	1.5	3.1	1.4	3.3	1.4	3.2	1.2	2.8	1.1	2.2	1.0	1.6
12	6.8	13.6	6.0	13.8	7.9	17.5	6.6	15.3	5.9	11.6	5.3	8.5
13	5.0	10.0	4.0	9.4	3.2	7.2	2.7	6.2	2.4	4.7	2.1	3.3
14	0.3	0.6	0.3	0.6	0.2	0.5	0.2	0.4	0.2	0.3	0.1	0.2
15	8.5	17.0	6.9	16.0	5.5	12.3	4.5	10.6	4.1	7.9	3.6	5.7
16	0.2	0.3	0.2	0.3	0.1	0.3	0.1	0.2	0.1	0.2	0.1	0.1
Total	50.1	100	43.2	100	44.9	100	42.9	100	51.2	100	62.7	100
λ_C	1.026		1.060		1.095		1.115		1.163		1.248	
λ_T	1.009		1.022		1.048		1.066		1.111		1.191	
λ_B	1.009		1.021		1.025		1.025		1.025		1.025	
λ_R	1.007		1.016		1.019		1.020		1.021		1.023	
ER	4.01		4.30		3.75		3.49		2.76		2.04	
Qc:	105,890		157,060		174,390		177,810		183,050		190,900	
POWER	7.12		8.97		10.19		9.81		11.65		14.10	
η_c	61.9		51.1		61.2		584		68.3		80.8	

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. 2 OF 2

DATE 5/15/73

COMPUTATIONS FOR SUMMARY OF TDT CIRCUIT LOSSES WITH FREON.

BY [signature] CHKD

TABLE 2

SECTION	P_t=2000 M=0.4		P_t=2000 M=0.7		P_t=1300 M=0.9		P_t=1100 M=1.0		P_t=950 M=1.1		P_t=700 M=1.2	
	ΔP_T	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%	ΔP_t	%
1	3.8	9.5	7.9	8.9	6.3	7.0	5.5	5.8	4.8	4.5	3.4	2.8
1a	1.3	3.3	2.8	3.1	2.1	2.4	1.9	2.0	1.6	1.5	1.1	0.9
2	7.4	18.6	15.9	17.9	12.2	13.6	10.5	11.1	9.0	8.4	6.2	5.3
3	0.1	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
4	0	0	0.1	0.1	0.1	0.1	0	0	0	0	0	0
5	1.7	4.2	3.8	4.3	2.9	3.2	2.5	2.6	2.2	2.0	1.5	1.2
6	0.4	1.0	0.9	1.0	0.7	0.7	0.6	0.6	0.5	0.5	0.3	0.3
7	0.4	1.0	1.0	1.1	0.9	1.0	0.9	0.9	0.8	0.7	0.6	0.6
8	4.3	10.8	10.5	11.8	9.9	11.0	9.6	10.0	9.2	8.5	7.5	6.4
9	1.7	4.2	3.5	4.0	5.2	5.7	4.9	5.2	4.7	4.3	3.7	3.1
9a	0	0	0	0	9.0	10.0	22.4	23.6	43.1	40.2	70.4	59.5
10	0.9	2.3	2.1	2.4	1.9	2.1	1.7	1.8	1.5	1.4	1.2	1.0
11	1.1	2.8	2.6	2.9	2.6	2.9	2.4	2.5	2.1	2.0	1.6	1.4
12	5.4	13.5	12.2	13.8	16.5	18.2	14.6	15.3	12.8	11.9	9.5	8.0
13	4.1	10.3	9.1	10.2	7.2	7.9	6.3	6.6	5.5	5.1	4.0	3.4
14	0.2	0.5	0.5	0.6	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.2
15	7.0	17.6	15.4	17.4	12.2	13.5	10.6	11.2	9.3	8.6	6.8	5.7
16	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
TOTALS	39.9	100	88.7	100	90.4	100	95.1	100	107.6	100	118.2	100
λ_c	1.020		1.046		1.073		1.092		1.123		1.192	
λ_T	1.007		1.016		1.036		1.053		1.083		1.150	
λ_B	1.008		1.016		1.020		1.020		1.020		1.018	
λ_R	1.006		1.013		1.016		1.017		1.017		1.018	
ER	4.15		4.76		4.23		3.81		3.16		2.28	
Q_c:	47,775		71,450		79,410		81,275		82,520		83,800	
POWER	2.56		8.40		9.38		10.00		11.25		11.94	
η_c	40.3		44.8		53.1		56.8		64.1		68.4	

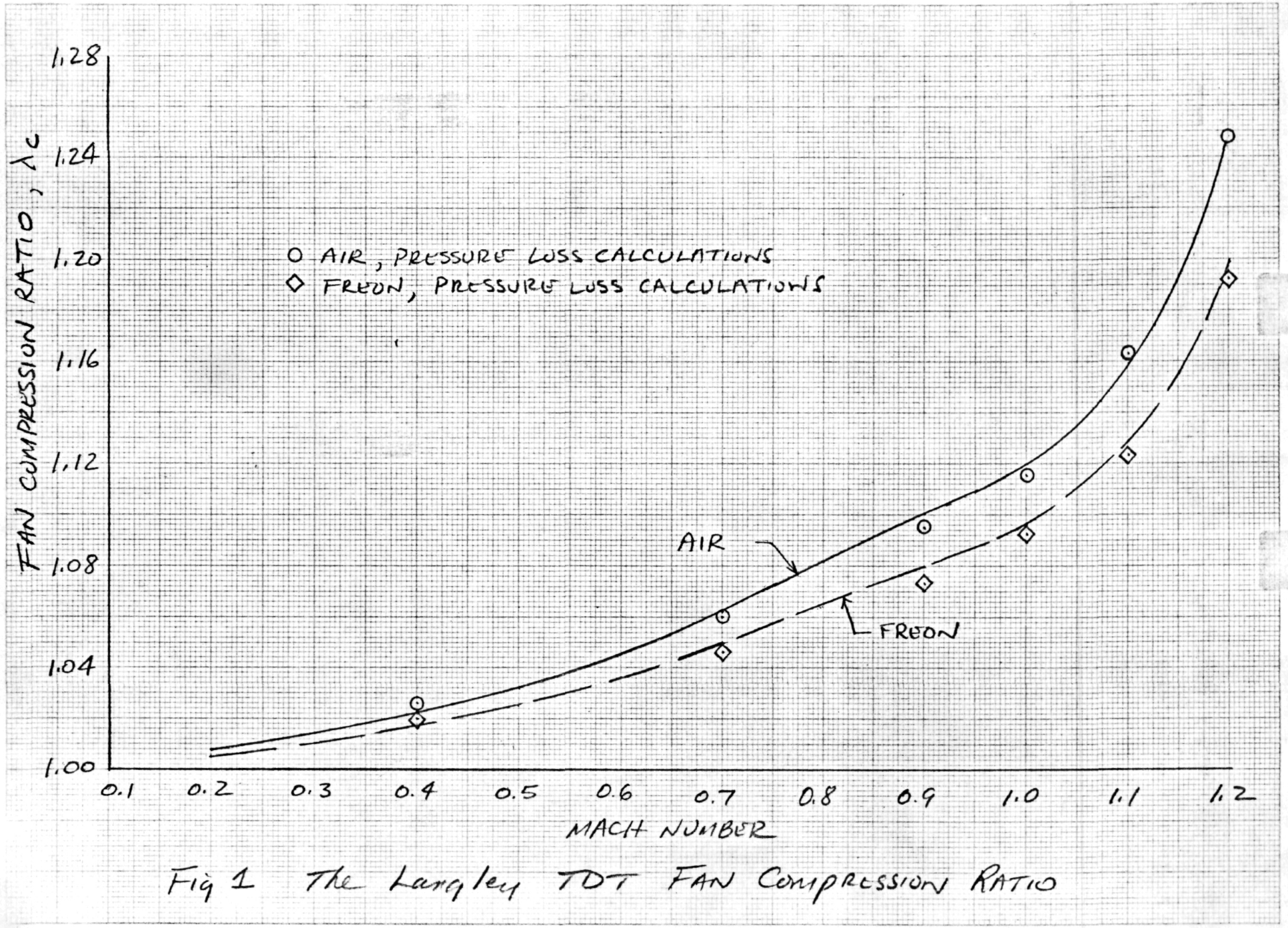


Fig 1 The Langley TDT FAN Compression Ratio

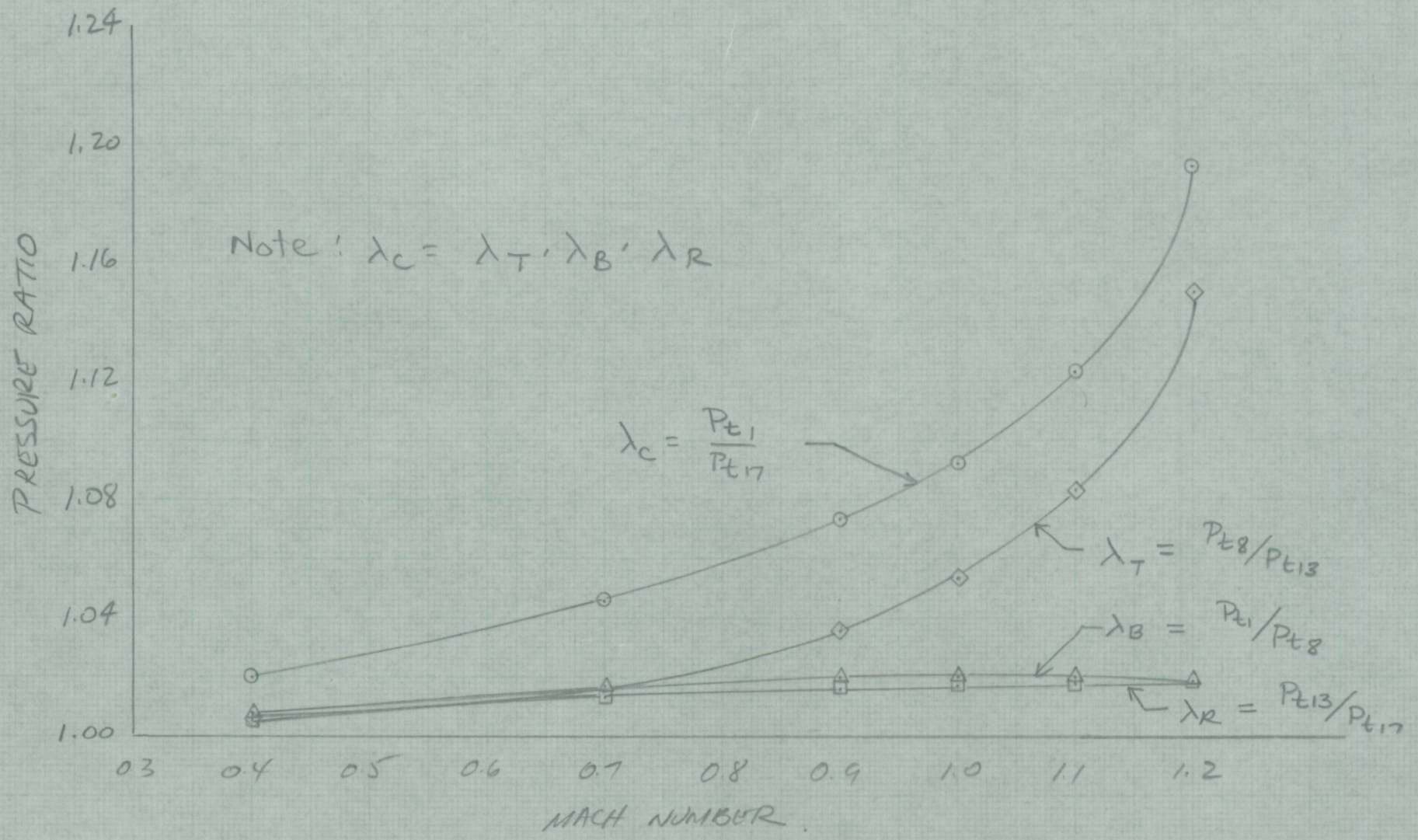


Fig 2. Various Circuit pressure ratios, Freon

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MILLIMETER
EUGENE DIETZGEN CO.
MADE IN U. S. A.

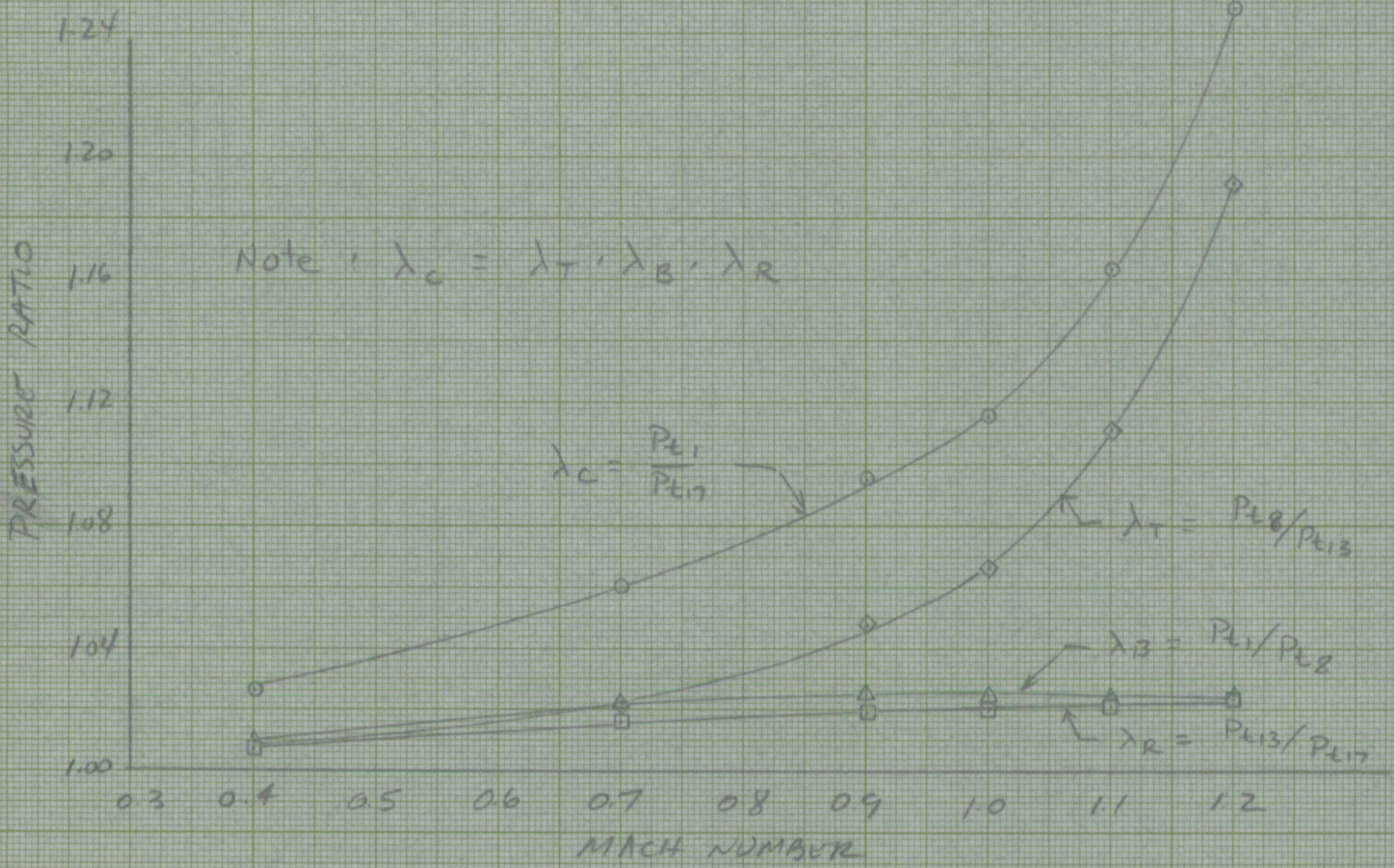

Fig 3. Various Circuit Pressures Ratios, Air

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Note : Total Power given in LWP-799

Δ POWER = BRAKE, RHEOSTAT AND AUXILIARY POWER

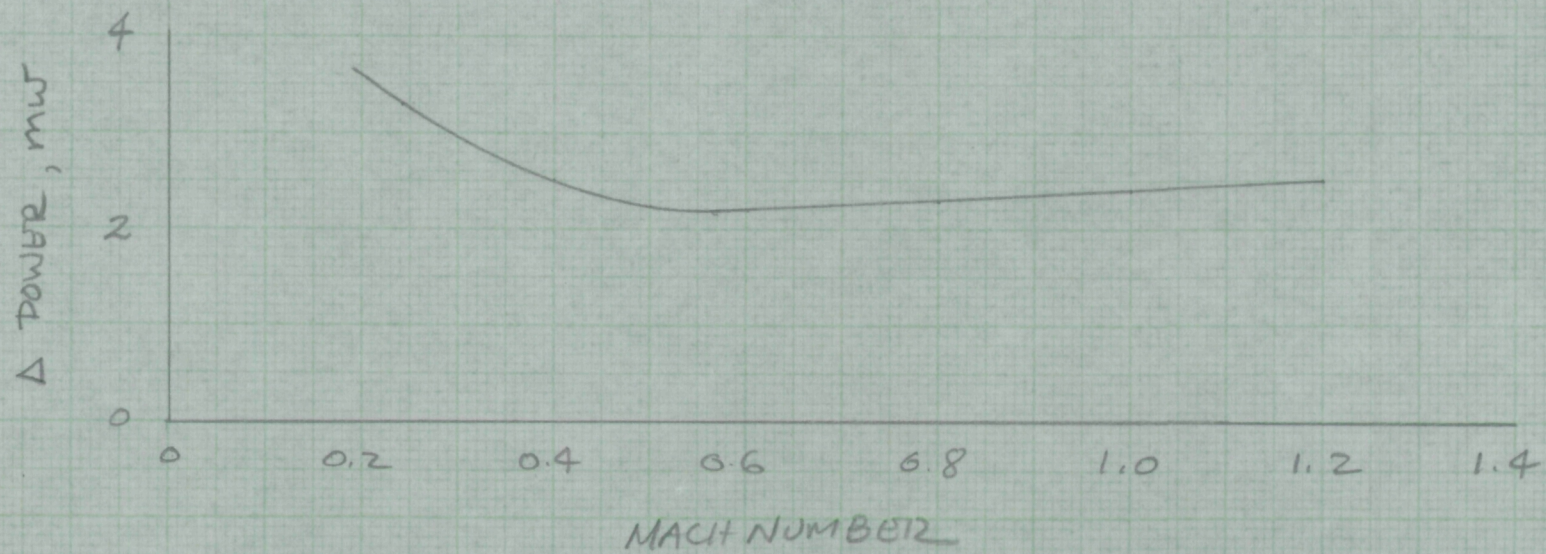

Fig. 4. Difference Between TDT Total and Main Drive Power

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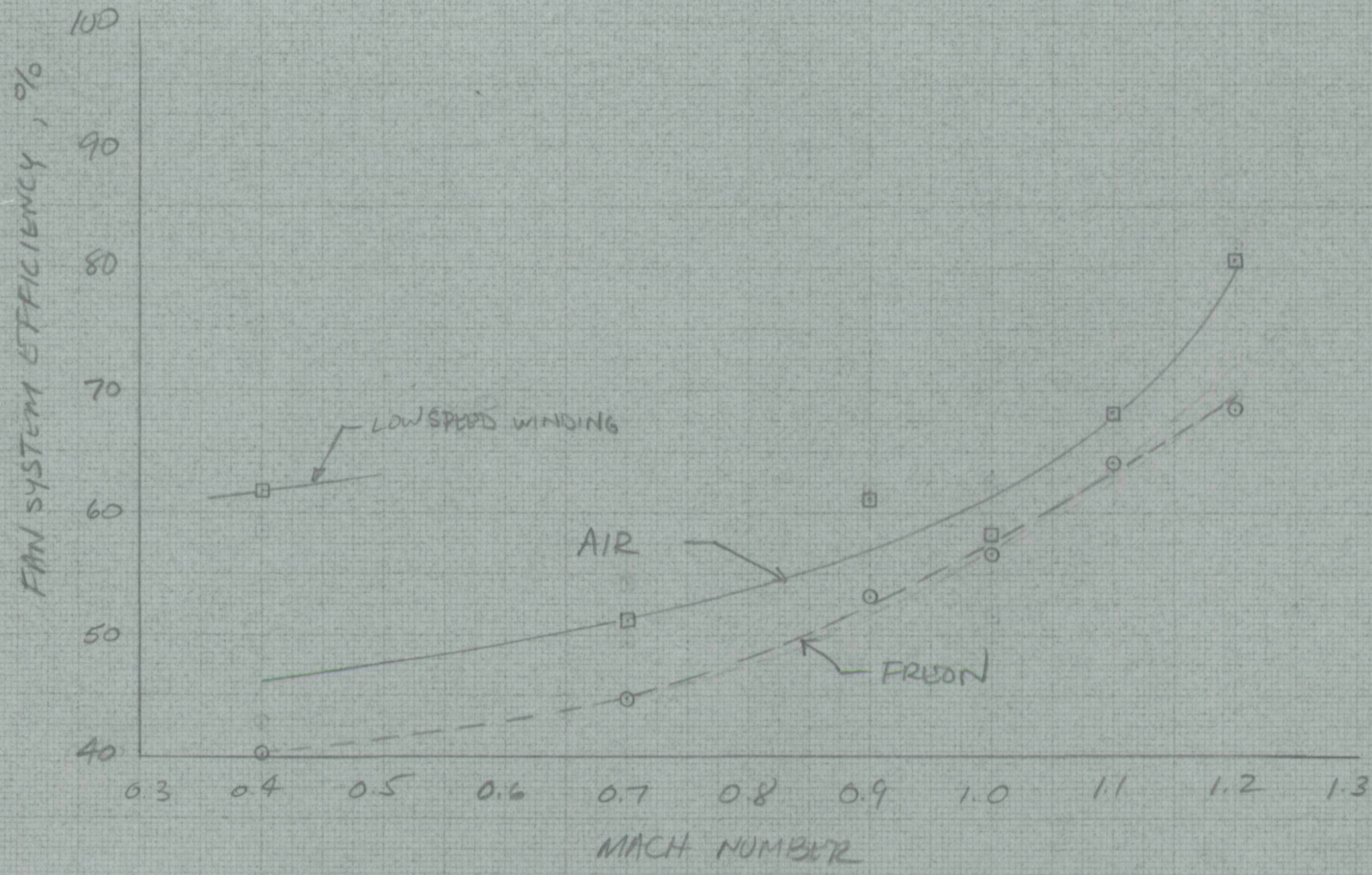

Fig. 5 Estimated TDT FAN EFFICIENCY

5/15/73
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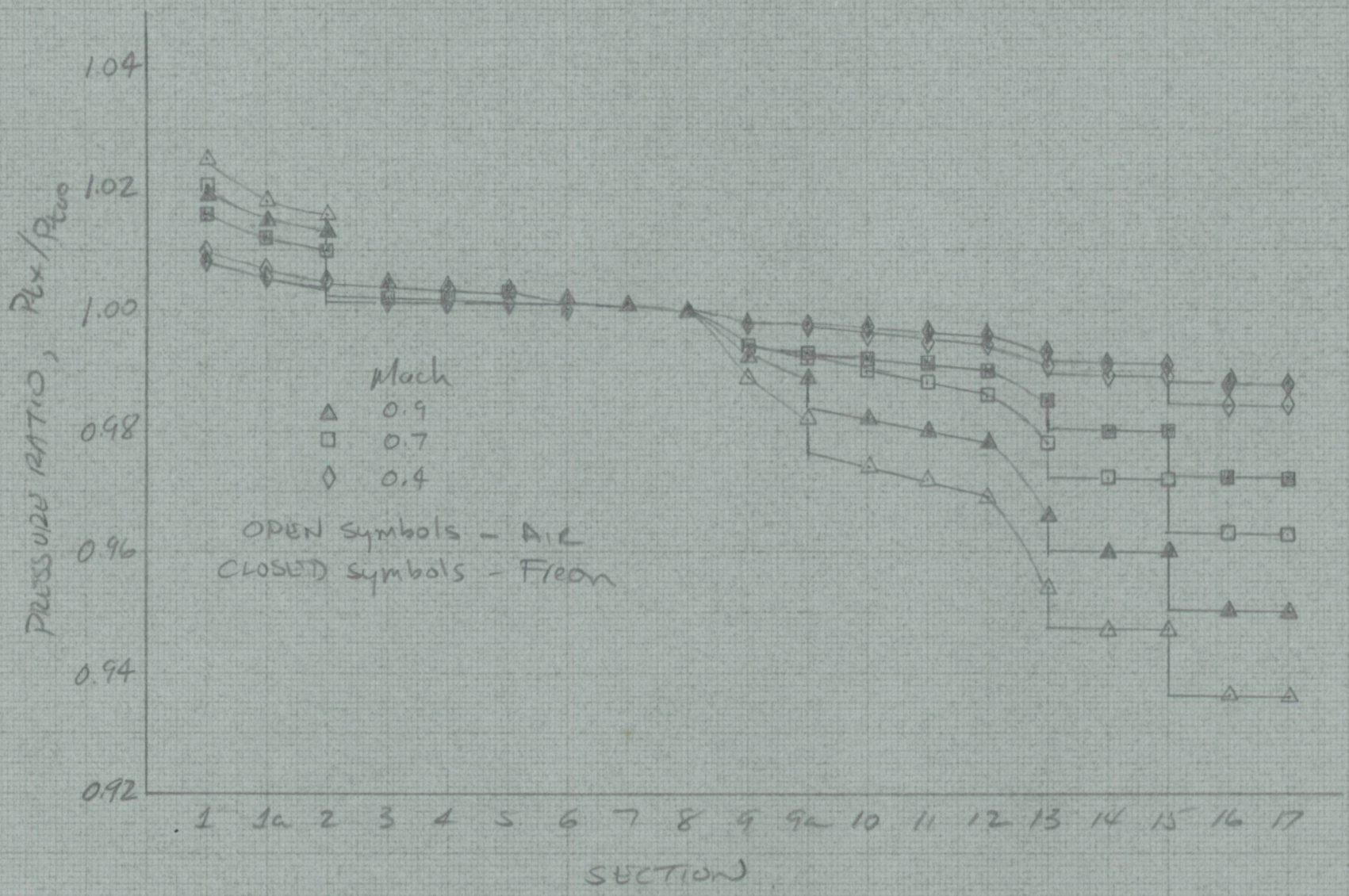

Fig. 6 Distribution of Total Pressure for the TDT Circuit at Mach Numbers of 0.4, 0.7 and 0.9

FMJ 5/15/73

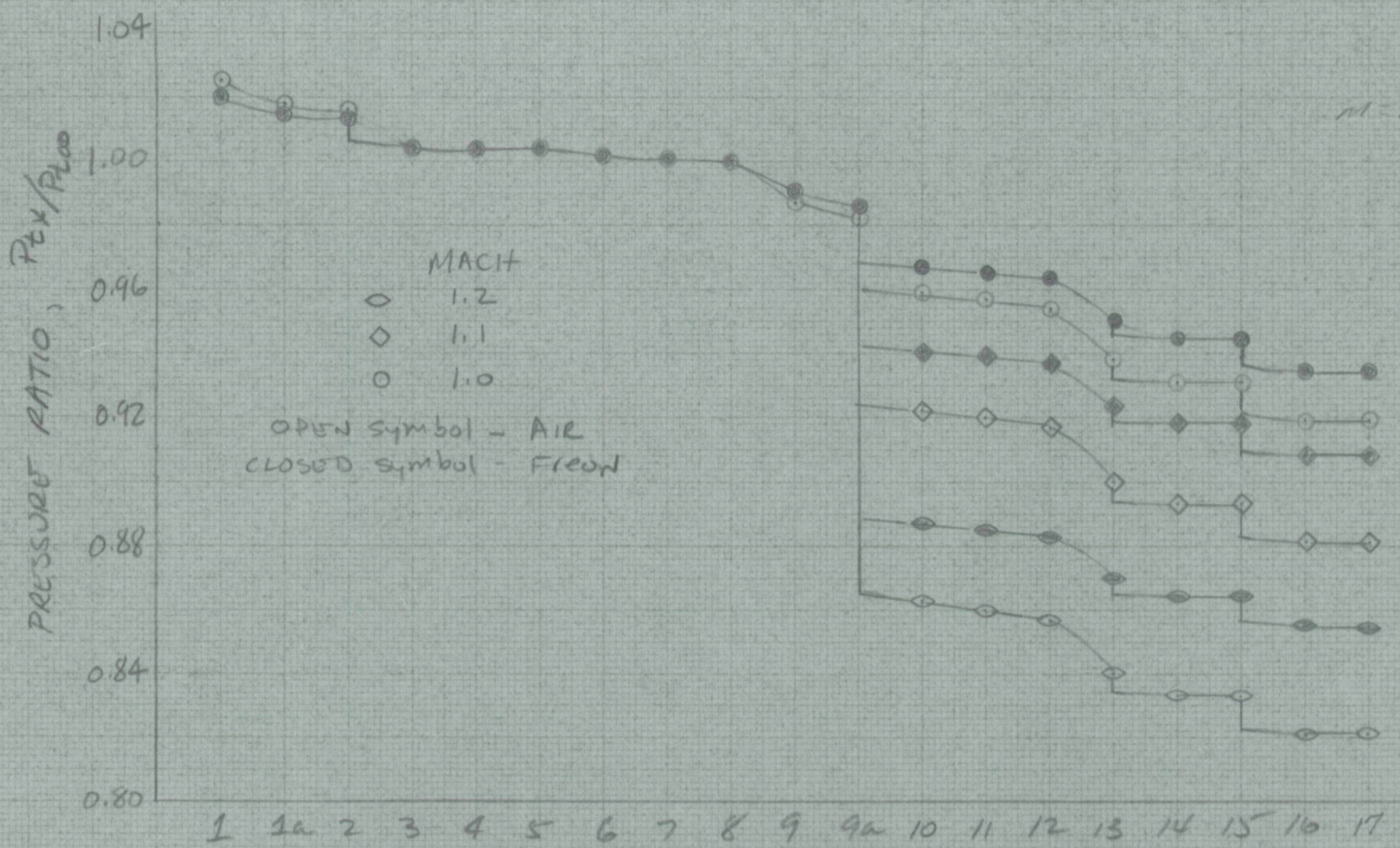

Fig 7 Distribution of Total Pressure for the TDT Circuit at Mach numbers of 1.0, 1.1 and 1.2.

FMJ
5/15/73

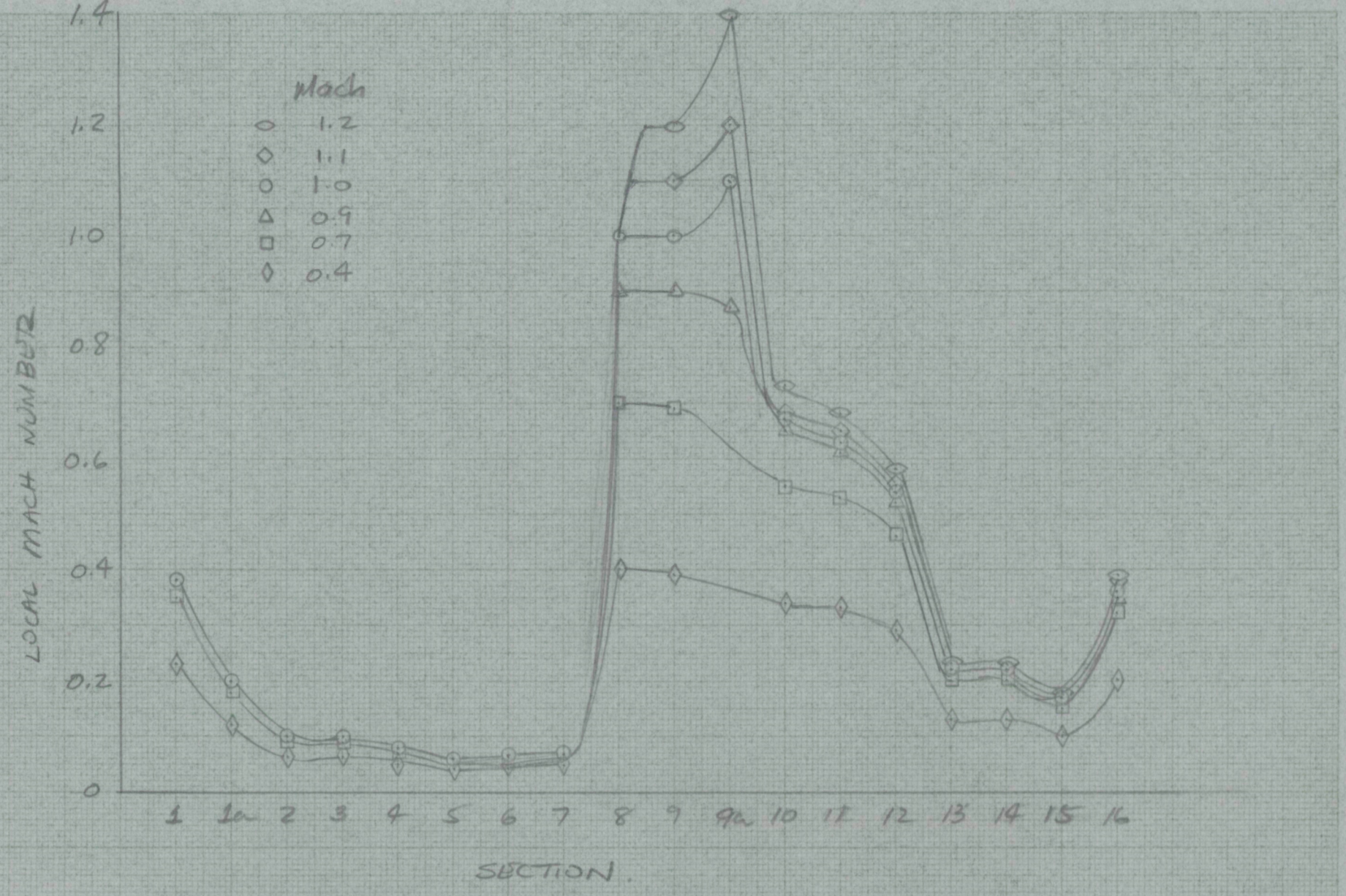

Fig 8 Distribution of Mach number for the TDT circuit, AIR AND Freon

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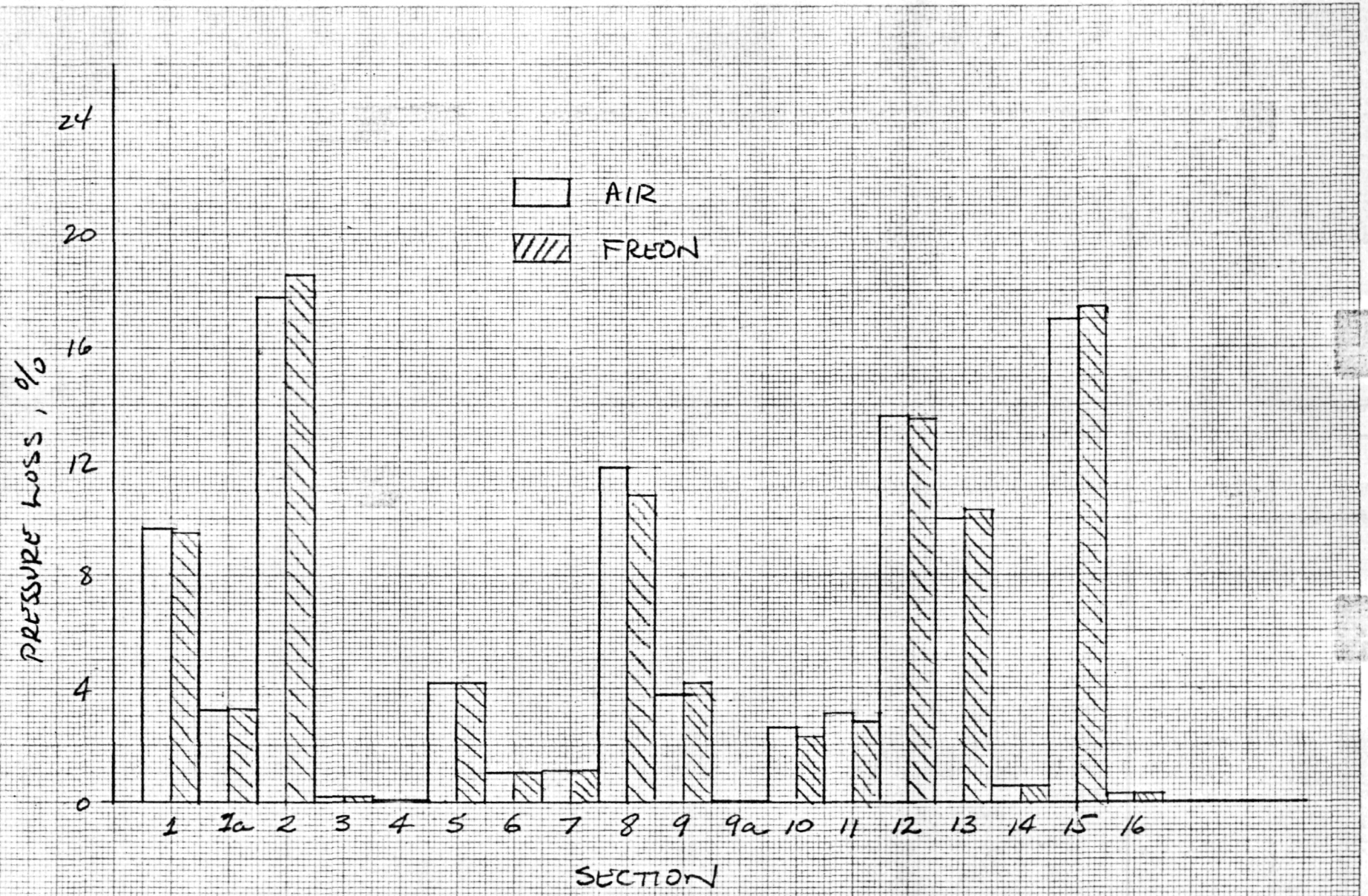

Fig. 9 Pressure Loss of Various Elements of the Langley TDT at $M_{\infty} = 0.4$ and maximum power.

FMS 5/15/73

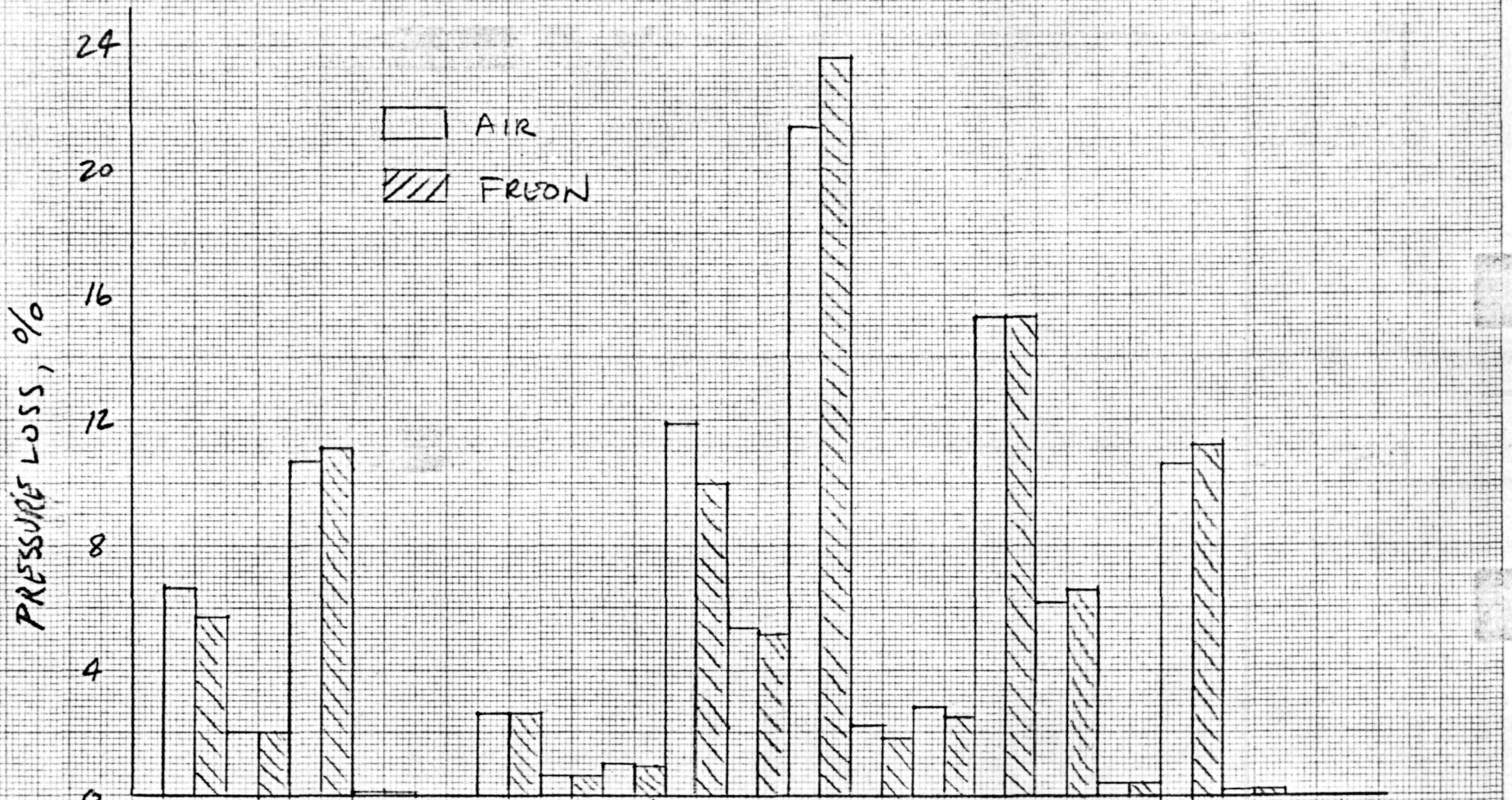

FIG 10 Pressure Loss of Various Elements of The Langley TDT at $M_\infty = 1.0$ and maximum power.

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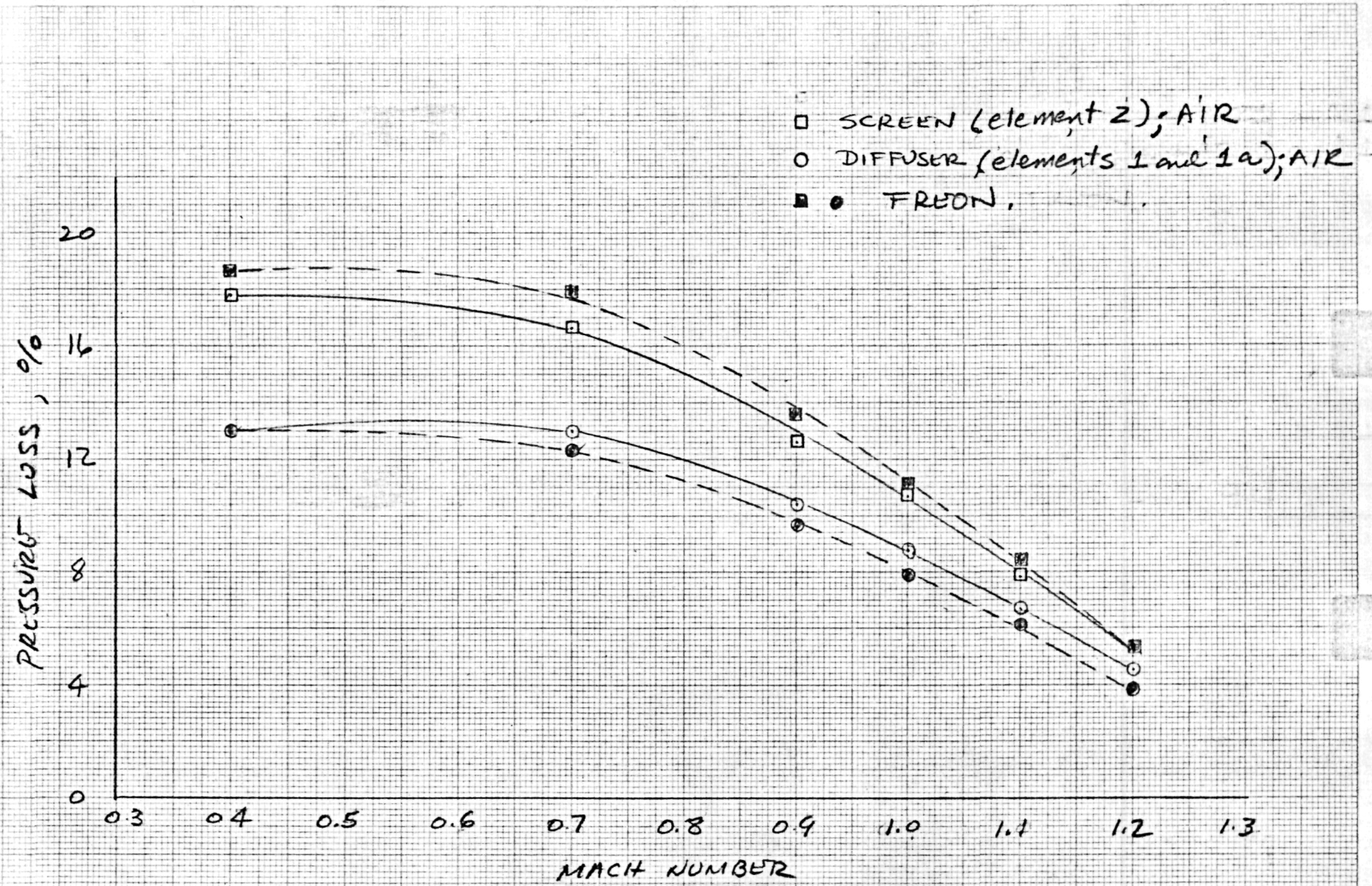

FIG. 11 Pressure Loss of the LANGLEY TDT East Leg Diffuser and Screen at various Mach numbers.

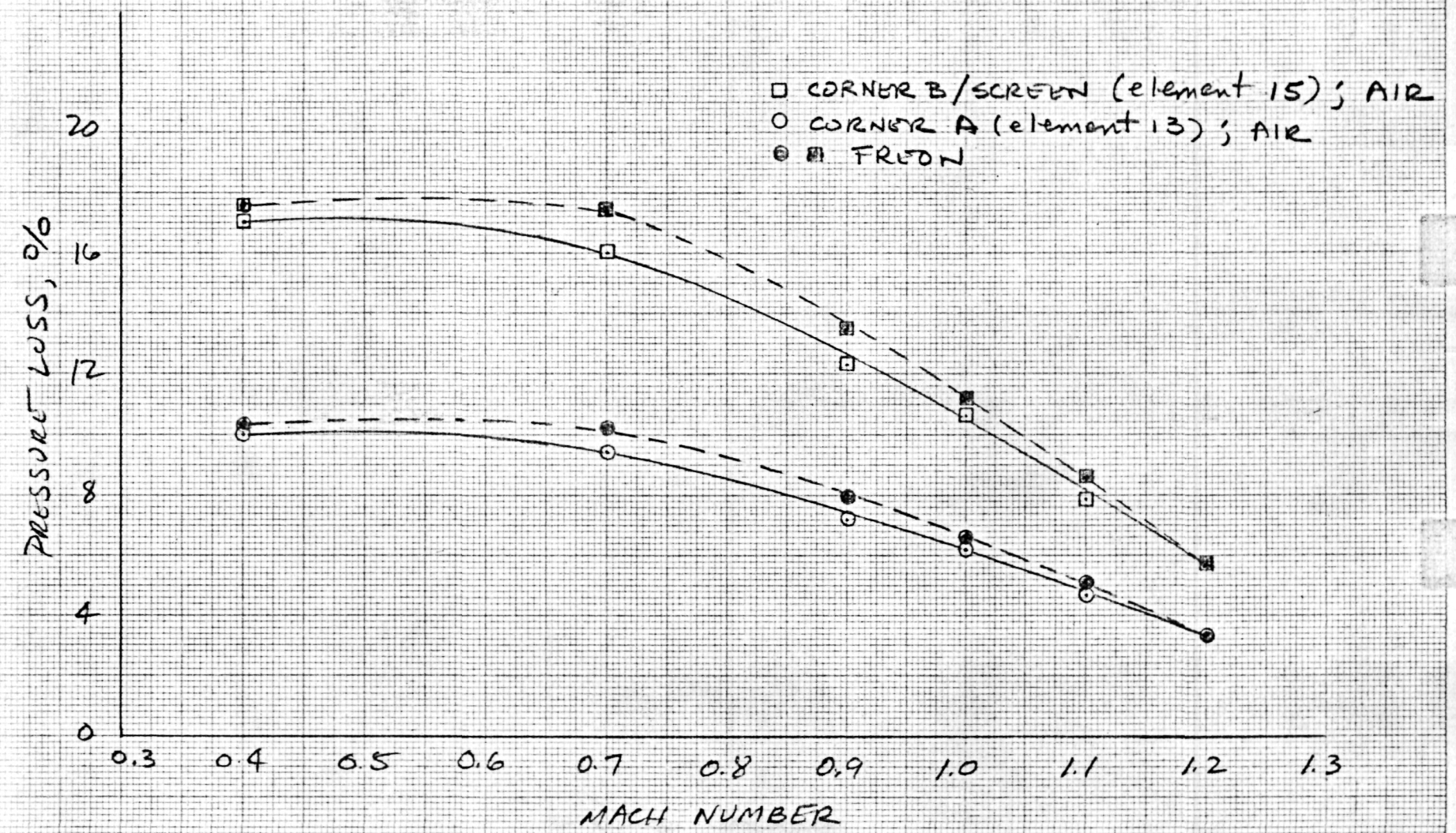

Fig 12 Pressure Loss of the Langley TDT Corner "A" and Corner "B" at Various Mach Numbers.

FMJ
5/15/73

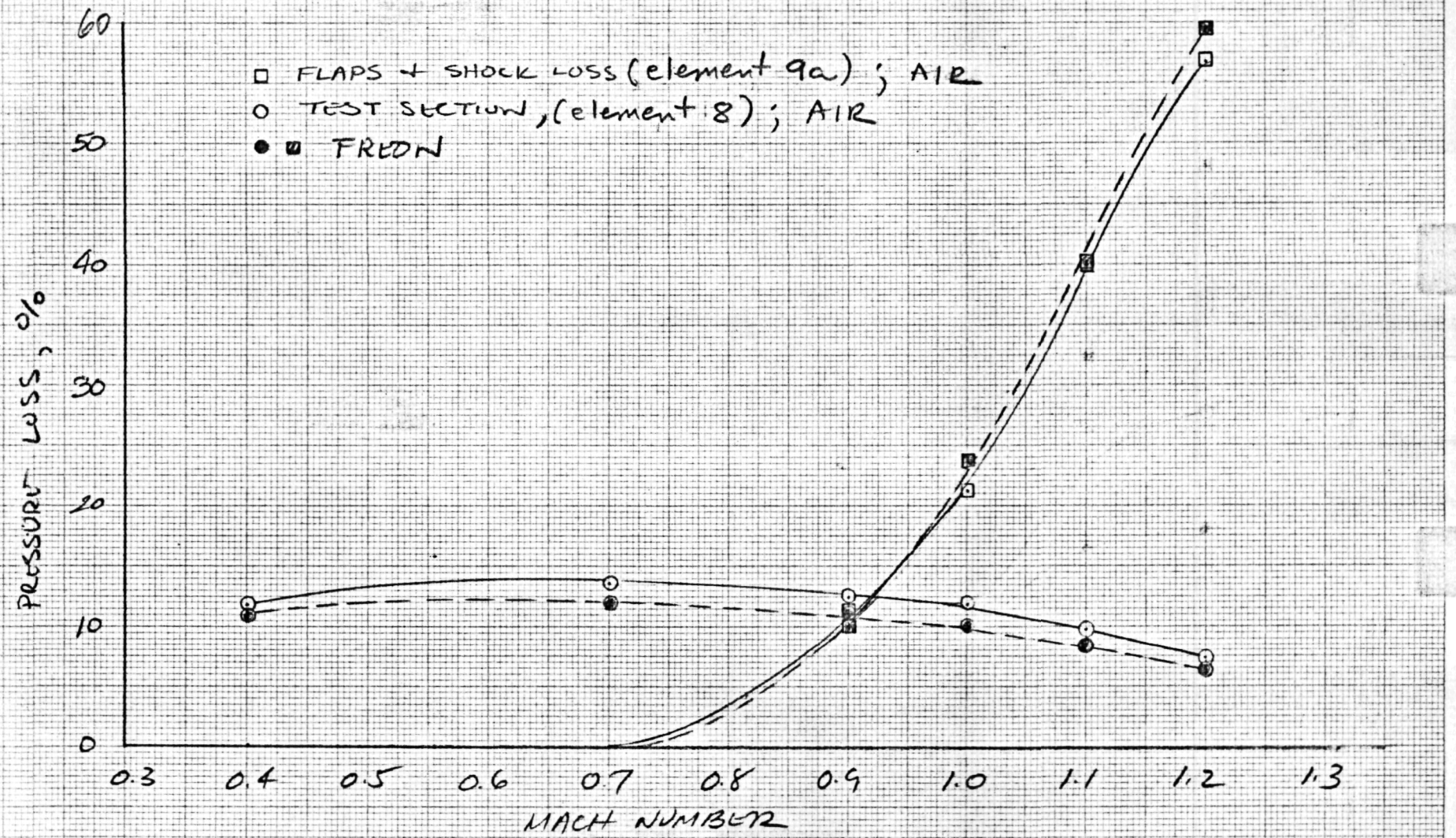

Fig 13 Pressure Loss of the LANGLEY TDT TEST SECTION AND FLAPS at VARIOUS MACH NUMBERS.

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5/15/73

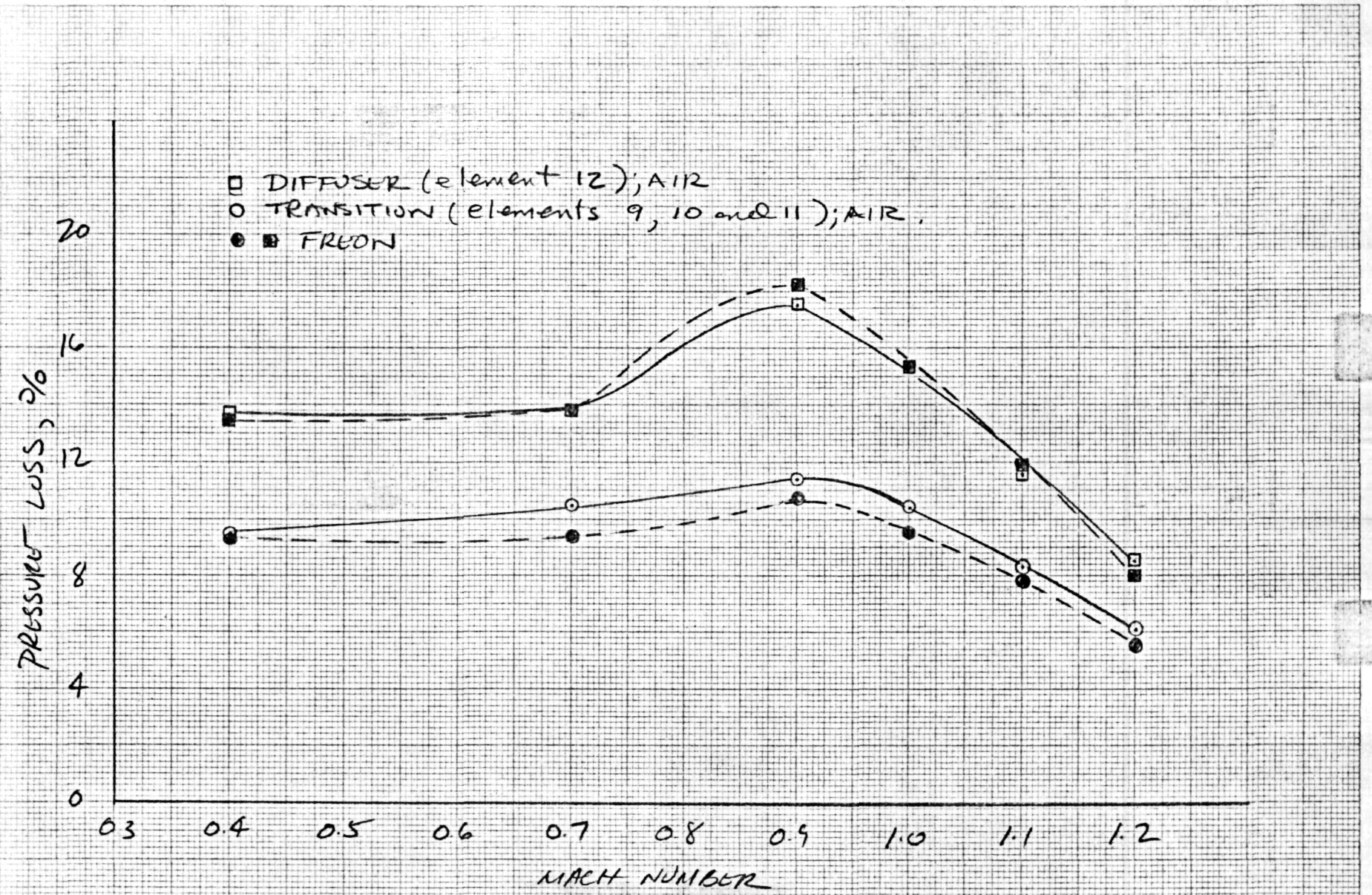

Fig. 14 Pressure Loss of the Langley TDT West Leg Diffuser and Transition at various Mach Numbers.

FMS 5/15/73

APPENDIX D

PROPOSED TEST PROGRAM

APPENDIX D

PROPOSED TEST PROGRAM

Although the pressure loss calculations provide a good indication of the losses for various circuit elements, it is considered prudent to base circuit modifications upon experimental data when possible. Consequently a test program to verify the TDT circuit losses and fan performance was recommended. Because of higher priority test programs for the Langley TDT the proposed test could not be run during the contract period of this study. All pre-test planning for the test, however, was accomplished. Consequently the test could easily be run at some future date should NASA officials desire to implement any of the recommendations of this study.

It was proposed that data be obtained at Mach numbers of 0.4, 0.7, 0.9, 1.0, 1.1 and 1.2 at maximum power with both Air and Freon-12 as a test medium. A total of 12 static pressure measurements were considered essential for the test. The desired location for these pressures were stations 0, 44, 80, 86, 96 129 and 214 on the west leg; station 0 on the North leg and stations 0, 12, 132, 76 and 0 on the East leg. In addition, the fan

inlet and exit temperatures and several other static and total pressures were suggested for a more detailed evaluation of the TDT performance. To aid the instrumentation setup, estimates of the static pressure around the circuit were made. These data are presented in Figs IV-1 and IV-2. Additional details on the proposed test instrumentation is presented in correspondence (dated October 25, 1972, January 10, 1973, March 15, 1973 and March 26 1973) between NASA and S&P representatives.

For evaluation of test results, several computer calculations were required. The data reduction equations and the required data tabulations are as follows:

Tunnel Static Pressures

Determine pressures in psf consistent with NASA transducer setup and data reduction. Designate scannivalve pressures for example, as SP191b, etc. Also, tabulate differential transducer readings (DP1 to DP10) and calculate ten pressures from the differential transducers and the scannivalve measured reference pressures. (Designate as P77b, etc) For example:

1) $P77b = SP191b + DP1$; etc. (Tabulate)

Mach Number at Station 44

2) $$M_{44} = \left\{ \left[\left(\frac{H}{P44} \right)^{\frac{\gamma-1}{\gamma}} - 1.0 \right] \frac{2}{\gamma-1} \right\}^{1/2}$$ (Tabulate)

where: γ = ratio of specific heats
H = stilling chamber total head pressure, psf
P_{44} = static pressure measured at Station 44, psf

for: Air $\gamma = 1.4$
Freon use Eqs. A8 and A9 from LWP-799 to solve for γ.

Tunnel Weight Flow

3) $$W = \dot{m} \frac{P44\, A44}{\sqrt{T_t}} \; ; \; \#/sec$$ (Tabulate)

where: T_t: tunnel stagnation temperature, °R
A_{44}: Station 44 area; 241.08 ft^2
$\dot{m}$: mass flow function for $M = M_{44}$ (see Eq. 4)

Mass Flow Function - General Form

4) $$\dot{m} = g\sqrt{\frac{\gamma}{R}}\, M\left[1 + \frac{\gamma-1}{2} M^2\right]^{1/2}$$

where: $g = 32.174 \ \frac{ft}{sec^2} \ \frac{\#m}{\#f}$

R = gas constant, $ft^2/sec^2 {}^\circ R$

for: Air $R = 1716.32 \ \frac{ft^2}{sec^2 {}^\circ R}$

Freon R varies with Freon purity. Determine from Ref. 16, 17 and 18 of LWP-799 or from mass balance.

Loss Calculations

Make calculations for Stations 191b, 77b, 0b, 44, 80, 96, 129, 214, 33c and 215b.

Mass Flow Function at Each Station

From Eq. 3 we have:

5) $$\dot{m} = \frac{W\sqrt{T_t}}{PA}$$ (Tabulate)

where: P is pressure measured at each station (Eq. 1)

A is the area at each station

and T_t = tunnel stagnation temperature (°R) for Stations 44, 80, 96, 129, 214, 33c and 215b.

T_t = compressor exit temperature (TTE) for Stations 191b, 77b and 0b, (°R)

Mach Number at Each Station

The Mach number at each station is determined by iterating Eq. 4 for $\dot{m}$ obtained from Eq. 5. For Air, use $\gamma = 1.4$ and R = 1716.32. For Freon use the Station 44 value of R and determine γ from Eq. A9 from LWP-799 using

6) $$T = T_t \left(\frac{P}{H} \right)^{\frac{\gamma_i - 1}{\gamma_i}}$$

where: γ_i is the value computed for Station 44
T_t from Eq. 5, °R
P is the pressure measured at each station (Eq. 1)
H is the stilling chamber total head pressure
T is to be used in Eq. A9 to find γ

NOTE: Tabulate γ for each station.

Total Pressure and Dynamic Pressure

For each station:

7) $$PT = P\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma - 1}} \quad ; \text{psf} \qquad \text{(Tabulate)}$$

and

8) $$Q = \frac{1}{2} \gamma P M^2 \quad ; \text{psf} \qquad \text{(Tabulate)}$$

where γ obtained from Eqs. 6 and A9 for Freon:
$\gamma = 1.40$ for Air
M is local Mach number (Eqs. 4 & 5)
P is the pressure measured at each station (Eq. 1)

NOTE: Designate total pressures as PT77b etc.
Designate dynamic pressures as Q77b etc.

Static Temperature

For each station:

9) $$T = T_t \left(\frac{P}{PT} \right)^{\frac{\gamma-1}{\gamma}} \quad ; {}^\circ R$$ (Tabulate)

where: T_t from Eq. 5 and PT from Eq. 7
γ is value computed for each station

Fan Pressure Ratio

10) $$FPR = \frac{PT191b}{PT215b}$$ (Tabulate)

PT191b and PT215b from Eq. 7

Section Pressure Losses

11) $$DPT(X) = PT(Y) - PT(Z) \quad ; psf$$ (Tabulate)

where:

X = 1	Y = 191b	Z = 77b
X = 2	Y = 77b	Z = 0b
X = 3	Y = 0b	Z = 44
X = 4	Y = 44	Z = 80
X = 5	Y = 80	Z = 96
X = 6	Y = 96	Z = 129
X = 7	Y = 129	Z = 214
X = 8	Y = 214	Z = 33c
X = 9	Y = 33c	Z = 215b
x = 10	Y = 215b	Z = 191b

Volume Flow

For each station:

12) $$VF = \dot{m} \frac{PRA}{g \cdot PT} \sqrt{T_t} \quad ; cfs$$ (Tabulate)

where: P is pressure measured at each station (Eq. 1)
A is area at each station
PT is total pressure at each station (Eq. 7)
$\dot{m}$ and T_t for each station from Eq. 5
For R and g see Eq. 4

NOTE: Designate volume flow as VF77b, etc.

Section Loss Coefficient

13) $KO(X) = \dfrac{DPT(X) \cdot VF(Y)}{Q44 \cdot VF44}$ (Tabulate)

Where: DPT (X) from Eq. 11 (exclude DP10)
Q44 from Eq. 8
VF from Eq. 12 where VF(Y) is volume flow at the entrance of the section i.e. for KO1: Y = 191b, etc.

Tunnel Energy Ratio

14) $ER = \dfrac{1}{\Sigma KO(X)}$ (Tabulate)

where: X = 1 to 9 (See Eq. 13)

Section Percent Loss

15) $SPL(X) = KO(X) \cdot ER \cdot 100 \quad ; \%$ (Tabulate)

Fan Adiabatic Efficiency

16) $FE = \dfrac{TTI\left[(FPR)^{\frac{\gamma-1}{\gamma}} - 1.0\right]}{TTE - TTI}$

where: TTI is fan inlet temperature, °R
TTE is fan exit temperature, °R
FPR from Eq. 10
γ is value calculated for Station 215b

Reynolds Number

For air:

17) $$\frac{Re}{\ell} = R_N = 1.2582 \times 10^6 \, M \cdot PT \left[\frac{T_t + 198.6 (1 + 0.2 M^2)}{T_t^2 (1 + 0.2 M^2)^{2.5}} \right] ; \frac{1}{ft}$$

where: M is Mach at each station

P_T from Eq. 7

T_t from Eq. 5

For Freon use P measured at each station (Eq 1), the Freon purity, X, and the static temperature at each station (Eq. 9) along with Eqs. A13 to A17 of LWP-799 to compute R_N.

NOTE: Tabulate R_N for each station.

Summary of Tabulated Data

In addition to NASA data requirements tabulate for each data point:

a) H, P (chamber), T_t, TTE and TTI
b) W, R, FPR, ER, X and FE
c) 20 scannivalve pressures (SP0 to SP194)
d) 10 differential pressures (DP1 to DP10)
e) 10 differential total pressures (DPT1 to DPT10)
f) 9 section loss coefficients (K01 to K09)
g) 9 section percent losses (SPL1 to SPL9)
h) A, γ, $\dot{m}$, M, P, T, PT, Q, R_N and VF for each of 10 stations (191b, 77b, 0b, 44, 80, 96, 129, 214, 33c and 215b)
i) If possible, it would be desirable to have fan RPM, input power and stator blade position; flap position; brake and auxiliary power.

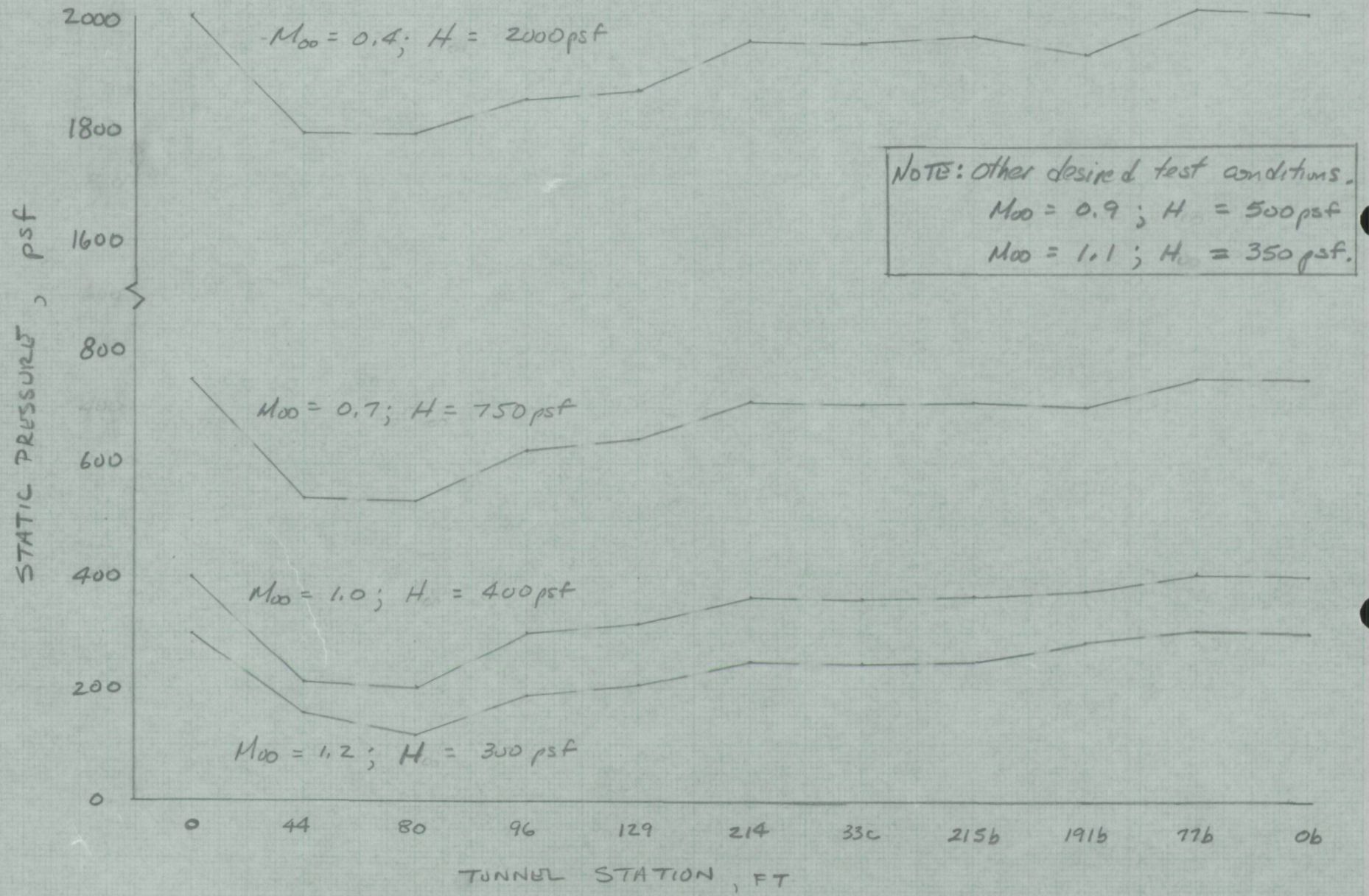

Fig. IV-1 Distribution of Static Pressure in TDT circuit with AIR at selected test conditions for loss study.

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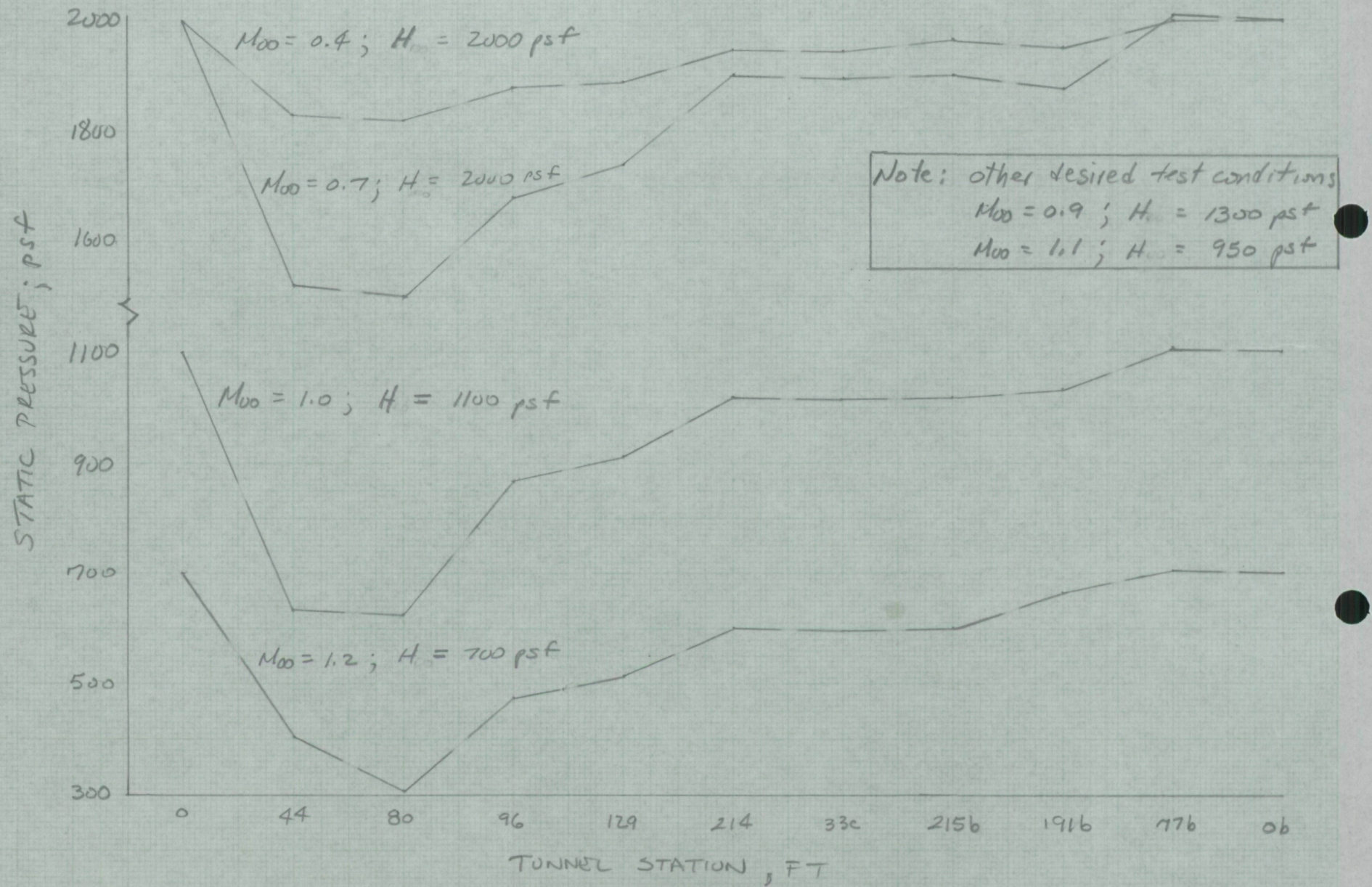

FIG IV-2 Distribution of Static Pressure in TDT circuit with Freon at selected test conditions for loss study.

FMJ 1/1/73

APPENDIX E

PERFORMANCE IMPROVEMENT
FOR
SEVERAL MODIFICATION METHODS

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. 1 OF 2

DATE 5/20/73

COMPUTATIONS FOR CORNER "B" SCREEN MODIFICATIONS.

BY JH Jackson CHKD

Assume that the fine mesh screen is replaced with one of 0.50 × 0.50 ; .031 diam

then $\beta' = \left(1 - \frac{.031}{.50}\right)^2 = 0.880$

and $K_T' \cong \left(\frac{1-\beta'}{\beta'^2}\right) = \frac{.12}{\beta'^2} = 0.155$

If we leave the Heavy screen the same and Assume that the K_T added. then

$$K'_{T_{total}} = 0.155 + 0.08 \doteq 0.24$$

$$\Delta K_{T_S} = K_T' - K_T \text{ (original value)} = -0.16$$

Then for the total corner $K_T = 0.44$
instead of 0.60 i.e. ~ 27% drop in ΔP

For Freon and $0.8 \leq M \leq 1.2$ the losses of the screen vary between ~ 16 and 6 % of the total losses (according to loss calculations) or 11.2 % at $M = 1.0$

Then if the screen is modified the losses and pressure ratio requirements would drop between 4.3 and 1.5 % for $M = 1.2$ to 0.8 and by 3.0 % at $M = 1.0$

The cost of the modification would be minimal, however the possible loss in "safety" might preclude making this modification.

However, the % improvement can be obtained as follows:

Now, the test section dynamic pressure may be written as:

$$q_\infty = \left(\frac{q}{P_t}\right)_M P_t = \frac{q}{P_t} \times P_{t_i} \times \lambda_c \times \frac{1}{\lambda_B}$$

and for $M = 1.0$ $\frac{q}{P_t} = 0.327$; $\frac{1}{\lambda_B} = 0.980$

and these are constant for screen changes.

In addition $P_{t_i}\left(\lambda^{\frac{\gamma-1}{\gamma}} - 1\right) \cong$ constant

for $M = 1.0$ $\lambda_c = 1.092$ for a 3% drop in losses $\lambda_c' = 1.089$

and $P_{t_i}' = P_{t_i}\left(\frac{.0101}{.0098}\right) = 1.031\, P_{t_i}$

and $P_{t_i}'\lambda_c' = 1.028\, P_{t_i} \times \lambda_c = P_{t_e}$

and $q_\infty' \cong \frac{q}{P_t}(1.028)\, P_{t_i} \times \lambda_c \times \frac{1}{\lambda_B} \cong 1.028\, q_\infty$

Conclusion at $M = 1.0$, we get 2.8% increase in q.

Note q_∞' is the improved condition.

Conclusion: Do not recommend modification.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 1 OF 5

COMPUTATIONS FOR MODIFICATIONS FOR SCREEN DOWNSTREAM OF FAN. DATE 5/21/73 BY [signature] CHKD

Ref: (1) Henry, John; Wood, C. and Wilbur S., "Summary of Subsonic Diffuser Data", NACA RM L56F05

(2) Schubauer G. B and Spangenberg N.G, "Effect of Screens in Wide Angle Diffusers NACA TN 1610.

The circuit pressure loss study, fig 11, 5/15/73 (see report fig 8) shows that for Freon the screen losses vary from 17.6% at M = 0.8 to 5.2% at M = 1.2 and are 11.1% at M = 1.0.

Three observations were made concerning possible modifications: They are as follows.

(1) The best diffuser performance is usually obtained when the screen is placed near the entrance of the diffuser, say at about $x/D = 1.0$. For the TDT, the screen is placed at $x/D_{eq} \cong 4.0$ if we assume the diffuser starts at about sta E175.

Because the Mach number increases as we move upstream on the nacelle, the pressure losses would probably increase if we moved the screen forward unless the screen porosity was also reduced.

(2) Because the effective diffusion angle of the annular diffuser between sta 132 and 50 is only about 12.5° it was believed that the porosity of the screen

(2) cont.

could actually be reduced. Considering the anticipated performance increase and that experimental data on the present setup should be obtained, a detailed analysis is beyond the scope of the study.

Assuming that a screen with $K_T = 1.0$ would be sufficient, a 37.5% drop in screen loss would be realized. Such a modification would drop the total losses and pressure ratio by 4.2 % at M=1.0.

Then for M=1.0 $\lambda_c = 1.092$ and $\lambda_c' = 1.088$

for which $P_{t_i}' = P_{t_i}\left\{\frac{(\lambda^{\frac{\gamma-1}{\gamma}}-1)}{(\lambda^{\frac{\gamma-1}{\gamma}}-1)'}\right\} = 1.042\, P_{t_i}$

for $q_{00} = \frac{q}{P_t} \times P_{t_i} \times \lambda_T \times \lambda_R$

Note: this neglects additive effects of loss reduction.

for M=1.0, $q/P_t = 0.327$, $\lambda_T = 1.053$, $\lambda_R = 1.017$

and $q_{00}' = \frac{q}{P_t}(1.041) P_{t_i} \lambda_T \times \lambda_R = 1.042\, q_{00}$

Considering the minimal cost of such a modification and the small improvement, no further discussion is warranted.

(3) In addition to a large pressure loss the screen can also lower the diffuser efficiency. of course the screen allows the diffuser to fill and thereby improving the velocity distribution. The possibility of replacing the screen with vortex generators on the nacelle and perhaps the wall was considered. The referenced material show that such installation can improve the velocity distribution and increase the diffuser efficiency above that with no vortex generators by at least 10%. (fig 16, H Taylor)

Based on the circuit losses the efficiency of the annular diffuser is as follows:

For $\eta = \frac{\Delta P}{\Delta q_0}$ (for Air)

$$\eta_{191-0} = \frac{406-376}{38-1} = \frac{30}{37} = 81\%$$

$$\eta_{132-0} = \frac{406-401}{11-1} = \frac{5}{10} = 50\%$$

If the screen were eliminated and assuming that the velocity distribution was such that no momentum losses occured the efficiency without the screen would be:

$$\eta_{NS\ 191-0} = \frac{410-376}{38-1} = \frac{34}{37} = 92\%$$

(3) Cont.

These data indicate that the efficiency of the diffuser can be improved by replacing the screen.

As previously stated the screen contributes to 11.1% of the circuit losses at M=1.0. If the screen were eliminated and vortex generators installation could preclude other significant losses, then a fair increase in performance could be obtained. For example if the modification was 75% effective then an 8% increase in performance would be available at M=1.0

The actual gain in performance is difficult to predict because it is subject to so many assumptions. The best approach is an experimental program, either on a full scale or model basis. It is believed that the TDT lends itself to full scale investigation of this possible modification. It is therefore recommended that a program be conducted in the TDT to investigate this possible improvement.

The program would include measurement of the annular diffuser efficiency and losses and the velocity Distribution at Sta E0. A suggested approach would be (a) install vortex generators (of conventional design) at about Sta E100. (b) remove the screen

(3) cont.

(c) if the effects of (b) are found to be detrimental, replace the screen mat with one of porosity about 1.0.

(d) if (c) was unsatisfactory return to the best configuration as indicated by the study.

The program which is described should provide a TDT performance improvement from 4 to 8% at M = 1.0, somewhat greater at M = 0.8 and somewhat less at M = 1.2. The cost of the proposed modifications are considered minimal and are therefore eliminated from this study.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

COMPUTATIONS FOR MODIFICATIONS TO FIRST DIFFUSER

SHEET NO. 1 OF 3

DATE 5/22/73

BY [signature] CHKD

1. What is effect of extending a splitter plate the length of the first diffuser?

This will effect element 12. Sta 129 - 214

Sta 12 : $A_{gross} = 319.6$

$A_{strut} = 1 \times 20.17 \cong 20.2\ ft^2$

$A_{NET} = 299.4\ ft^2$

with splitter plate $A_{①} = \frac{A}{2} = 149.7$

and $Deg_{①} = 13.80$

Sta 13 : $A_{gross} = 695.8$

$A_{strut} = 1 \times 29.76 = 29.8$

$A_{net} = 666\ ft^2$

with splitter plate $A_{②} = \frac{666}{2} = 333\ ft^2$

and $Deg_{②} = 20.59$, $L = 85$

Now $2\theta = 2 \tan^{-1} \frac{De_2 - De_1}{2L} = 4.6°$

and $K_{T_{fixed}} = K_D \left[1 - \frac{A_1}{A_2}\right]^2$

for $K_d = 0.13$ $K_{T\,fixed} = .0394$

$\Delta K_{T\,fixed} = .039 - .038 = +.001$

$D_{H①} = \frac{4 \cdot A/2}{\frac{\pi D}{2} + D} = \frac{4A}{\pi D + 2D} = 11.54$; $D_{H_2} = 17.41$

$D_{H\,Avg} = 14.48$ $K_{T_{friction}} = \lambda \frac{L}{D}$

$\Delta K_{T_{friction}} = 5.87\lambda - 3.40\lambda = {}^{+}2.5\lambda$

These data indicate that the losses would actually increase if a splitter plate were installed. This is not to suprising since the diffuser can not be considered a wide angle diffuser.

2. What would be the effect of vortex generator installation in the first diffuser?

REF: Taylor H.D., "Application of Vortex Generator Mixing Principle to Diffusers" UAC Report R-15064-5

The referenced material indicates that up to a 20% gain in diffuser performance can be obtained by installation of vortex generators in the diffuser. Futhermore a diffuser length can be shortened as much as 50% below the optimum without significant loss in efficiency. This would indicate that since the TDT diffuser was built at least 68' too short, that vortex generators should be installed.

Based on the circuit losses for From the efficiency of the diffuser at $M = 1.0$ (assuming Sta 129 as the entrance ~ 96 might be better) is:

$$\eta = \frac{1024 - 904}{150 - 28} = 98\%$$

This would not indicate that much improvement can be obtained for efficiency.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 3 OF 3

COMPUTATIONS FOR MOD - TO FIRST DIFFUSER BY [signature] CHKD DATE 5/22/73

IF we assume that the vortex generator application would inhibit flow separation which was assumed to occur for Mach numbers above 0.7. and that the adelative effects of loss reduction can be neglected we can evaluate possible performance increase as follows:

For From the circuit losses show the transition losses to vary between 5.5 and 10.5 %, being 9.5% at M = 1.0 and for the diffuser to vary between 8 and 18 % being 15.5% at M = 1.0.

If separation is eliminated at M = 1.0, the transition losses are reduced by 18% resulting in a 1.7% decrease in total losses. and the diffuser losses are reduced by 39% resulting in a 6% decrease in total losses.

Because of the minimal cost and % possible improvement and because it is probable that separation (if it exists) can not be eliminated as long as flap suction is utilized no further discussion is warranted.

It is recommended that NASA try installation of vortex generators and observe the effect on performance. It would appear that about Sta 109 would be a good place for generator installation. A suitable vortex generator design is easily obtainable from available literature.

The theoretical input power requirements for a closed circuit wind tunnel may be defined as:

$$(1) \quad HP = \frac{\gamma}{(\gamma-1)\,550} \frac{P_{ti}\, Q_c}{\eta_c} \left(\lambda_c^{\frac{\gamma-1}{\gamma}} - 1 \right)$$

where λ_c is the fan compression ratio

η_c is the fan system efficiency (ie. fan and motor)

P_{ti} is the fan inlet pressure, psf.

Q_c is the fan inlet volume flow, cfs.

Noting that $\lambda_c = \frac{P_{te}}{P_{ti}}$ and rearranging the eq we define a HP function as:

$$(2) \quad \frac{HP \cdot \eta_c}{P_{te}} = \frac{\gamma}{(\gamma-1)\,550} \frac{Q_c}{\lambda_c} \left(\lambda_c^{\frac{\gamma-1}{\gamma}} - 1 \right)$$

where P_{te} is the fan exit pressure;

Note: $P_{te} = \lambda_B P_{to_\infty}$ where

P_{to_∞} is the tunnel stagnation pressure

λ_B is the backleg pressure ratio. (see fig 2 and 3, "Tunnel Circuit Losses" 5/15/73).

We note from eq 2 that for a given pressure ratio and volume flow, the HP function is a constant. For $\gamma = 1.40$ for Air and 1.13 for Freon we obtain solutions to eq 2 as shown in Figs 1 and 2.

The TDT fan compression ratio has been estimated by earlier work ("Aux System Compression ratio", 11/17/72) This estimate was verified by the circuit pressure loss calculations (see fig 1, Tunnel Circuit Losses 5/9/73) The variation of pressure ratio with Mach number is presented in fig 3.

The compressor inlet volume flow is defined as:

$$(3) \qquad Q_c = \frac{W R T_t}{g P_{t_i}}$$

where W (weight flow) $= \dfrac{\bar{m} P_{t_\infty} A}{\sqrt{T_t}}$

where A is the Test Section Area

and $\bar{m} = \dot{m} \dfrac{P}{P_t} = g \sqrt{\dfrac{\gamma}{R}} M \left[1 + \dfrac{\gamma - 1}{2} M^2\right]^{-\frac{\gamma+1}{2(\gamma-1)}}$

Note! Tabulation of the $\bar{m}$ & $\dot{m}$ functions for Air are found in OAL memorandum 50, 1952. These parameters for 95% purity Freon $\gamma = 1.13$ & $R = 427$ are presented in Fig 4.

Rearranging eq 3 and noting that

$$\frac{P_{t_{oo}}}{P_{t_i}} = \frac{P_{t_{vo}}}{P_{t_d}} \cdot \frac{P_{t_d}}{P_{t_i}} = \lambda_T \cdot \lambda_R$$

we write:

$$(4) \quad Q_c = \frac{\bar{m} R A \sqrt{T_t}}{g} \lambda_T \cdot \lambda_R$$

Eq 4 indicates that Q_c is a function of Mach number, medium temperature and the pressure losses between the tunnel nozzle and the compressor inlet. It is convenient to define the tunnel "resistance line" as:

$$(5) \quad \frac{Q_c}{\lambda_T \cdot \lambda_R} = \bar{m} R A \sqrt{T_t}$$

The variation of the TDT "resistance line for $T_t = 125°F$; $A = 241.08$, for air and for Freon of 95% purity is presented in Fig 5.

Noting that $\lambda_T \cdot \lambda_R = \lambda_C / \lambda_B$ and using estimates of λ_B from the circuit loss study and taking λ_C from fig 3 we obtain the TDT fan operating lines as shown in Fig 6.

If the FAN system efficiency is known the data presented in fig 1, 2 3 and 6 can be used to predict main drive performance. The efficiency for the TDT was not supplied by NASA. An indication of the efficiency was obtained from the circuit loss analysis. These data however are not considered good enough to use for a final performance estimate for the various TDT modification alternatives. Consequently it will be assumed that the compressor system efficiency will remain constant.

Then from eq 2 we note for a given Mach number and pressure ratio the fan exit pressure and therefore the tunnel dynamic pressure, is directly proportional to the main drive power.

Then for 30,000 hp the dynamic pressure will be 1.5 times that at 20,000 HP. (Note this assumes no change in circuit losses hence no change in λ_c and Q_c) For a 50,000 hp new motor the performance will be 2.5 times the present performance.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY SHEET NO. 5 OF 6

COMPUTATIONS FOR TDT PERF. FOR INCREASED MAIN DRIVE POWER DATE 5/28/73 BY FDJ CHKD

Using data obtained from LWP-799 for the 18 mw normal performance we obtain the following scaled performance for the Mach number range 0.7 to 1.2.

Mach	FREON			AIR		
	q_b	$1.5q_b$	$2.5q_b$	q_b	$1.5q_b$	$2.5q_b$
0.7	350	525	875	146	219	365
0.8	348	522	870	141	212	353
0.9	340	510	850	133	200	333
1.0	325	487	812	124	186	310
1.1	300	450	750	113	170	283
1.2	240	360	600	100	150	250

The present tunnel pressure operating limit is 2120 psf. The shell structural limit is 2500 psf. The dynamic pressures corresponding to these limits and 125 and 150% shell limit for Freon are:

Mach	q/P_t	q_b, psf $P_t = 2120$	q_b $P_t = 2500$	q_b $P_t = 3125$	q_b $P_t = 3750$	
0.7	.2473	524	618			
0.8	.2939	623	735			⇐ AIR
0.9	.3352	711	838			
1.0	.3698	784	924			
1.1	.3967	841	992			
1.2	.4157	881	1039			
0.7	.211	447	528	660	790	
0.8	.255	541	638	797	956	⇐ FREON
0.9	.292	619	730	912	1092	
1.0	.327	693	818	1020	1225	
1.1	.354	750	885	1108	1325	
1.2	.374	793	935	1170	1400	

The estimated performance for the TDT for the proposed 30,000 HP rewired option and the 50000 HP new motor option is shown in Fig. 7 and 8 for Air and Freon, respectively.

The data in Fig 7 indicates that the nipercial performance is well within the present pressure operating limits for the TDT for the Mach range from 0.8 to 1.2.

The data in Fig 8 indicates that the performance with the 30,000 hp option is within the present pressure operating limits for the Mach number range 0.8 to 1.2. New manometers would allow operation down to M=0.7, however for M<0.7 the tunnel would have to be operated at a pressure higher than the 100% structural limit.

The data in Fig 8 also indicates that for the 50,000 hp option, that, even with new manometers, the tunnel will have to be operated at a pressure higher than the 100% structural limit for M<1.0. The data indicate that 138% of limit is required to utilize the 50,000 HP for the Mach number range 0.8 to 1.2. The tunnel shell structural analysis indicated that the tunnel could operate at 125% limit without significant modification. This would allow operation down to M = 0.85.

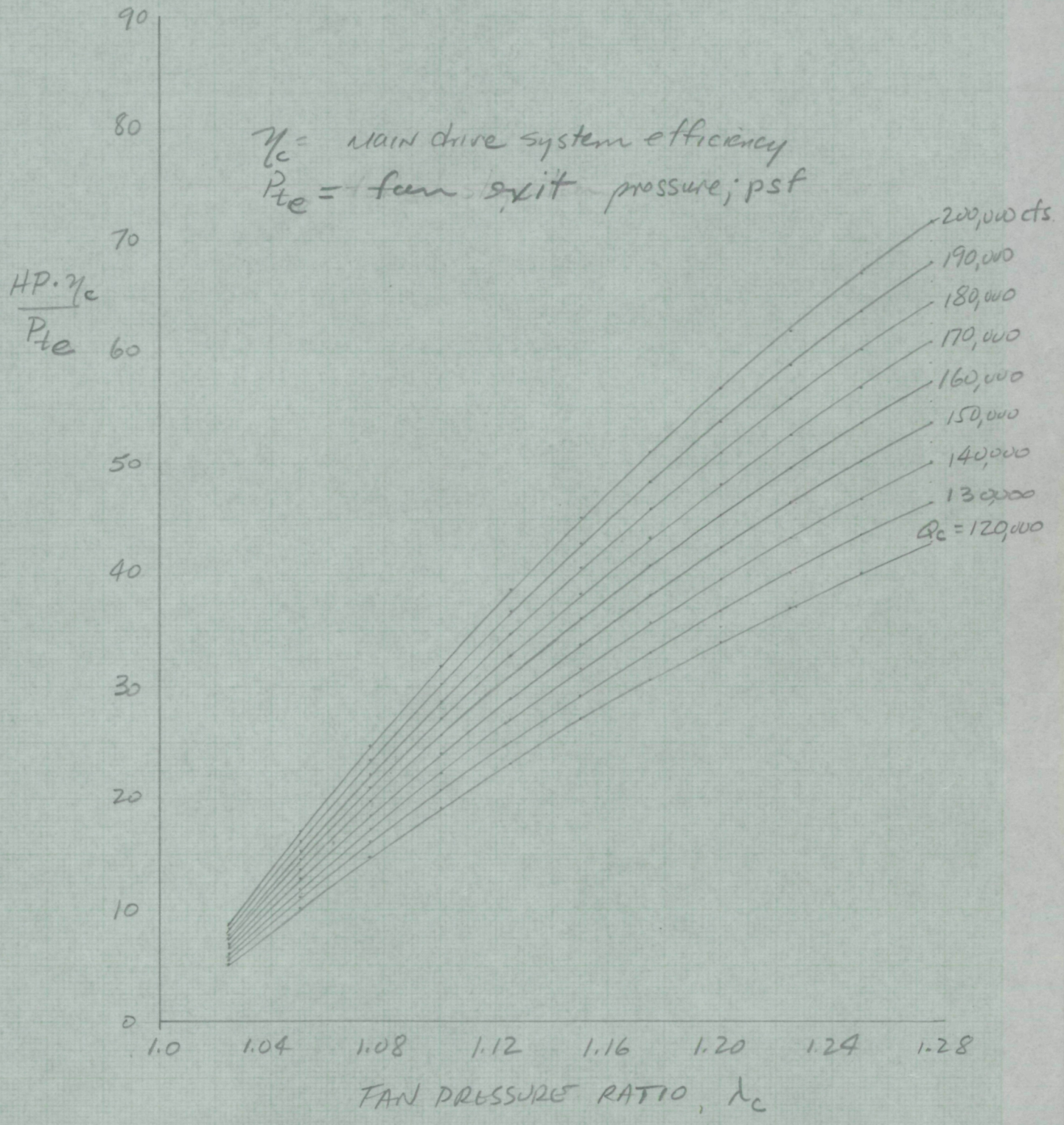

Fig 1 Power Requirements of Main Drive with Air.

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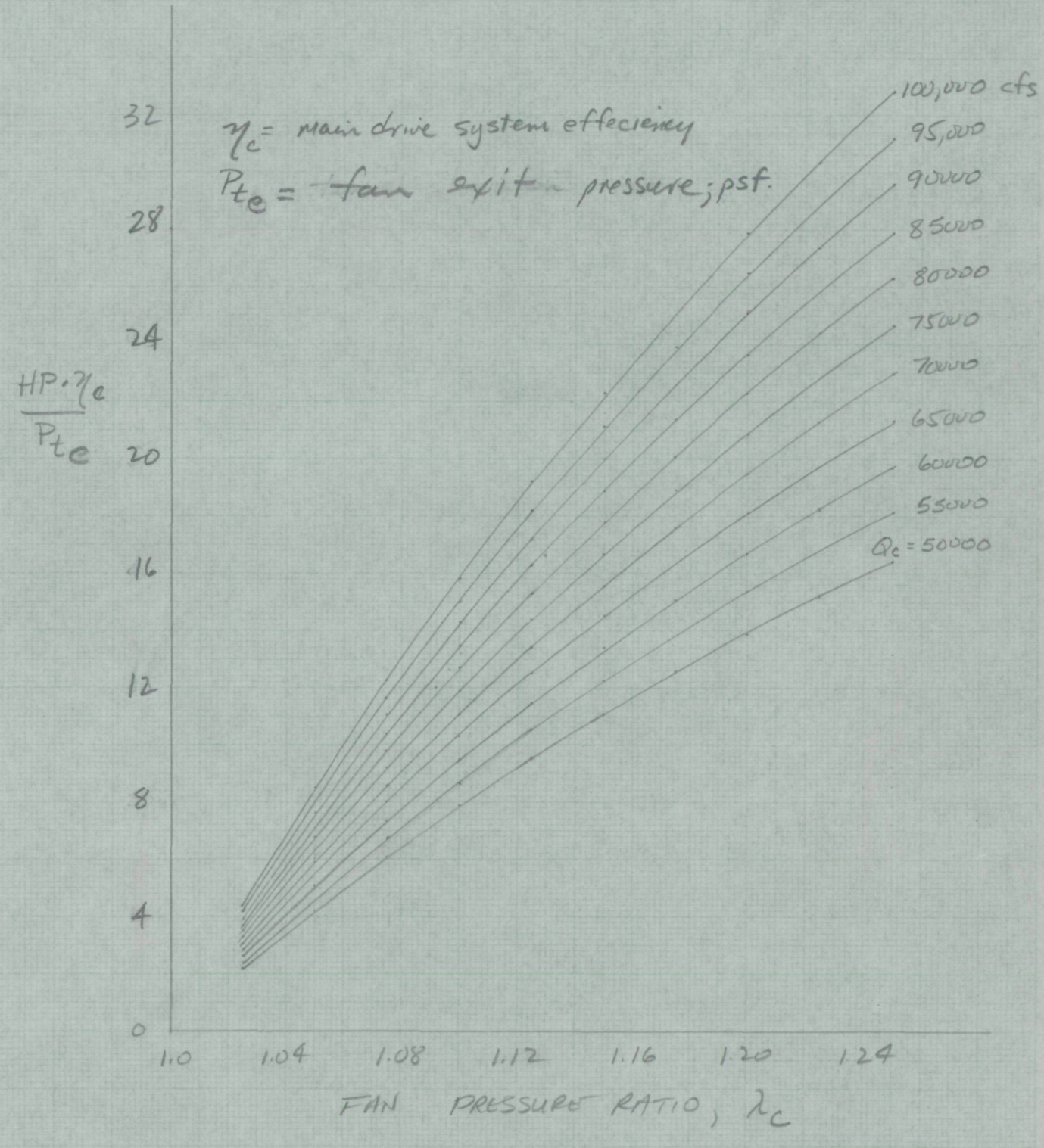

Fig 2. Power Requirements of Main Drive with Freon

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Fig 3. TDT FAN COMPRESSION RATIO.

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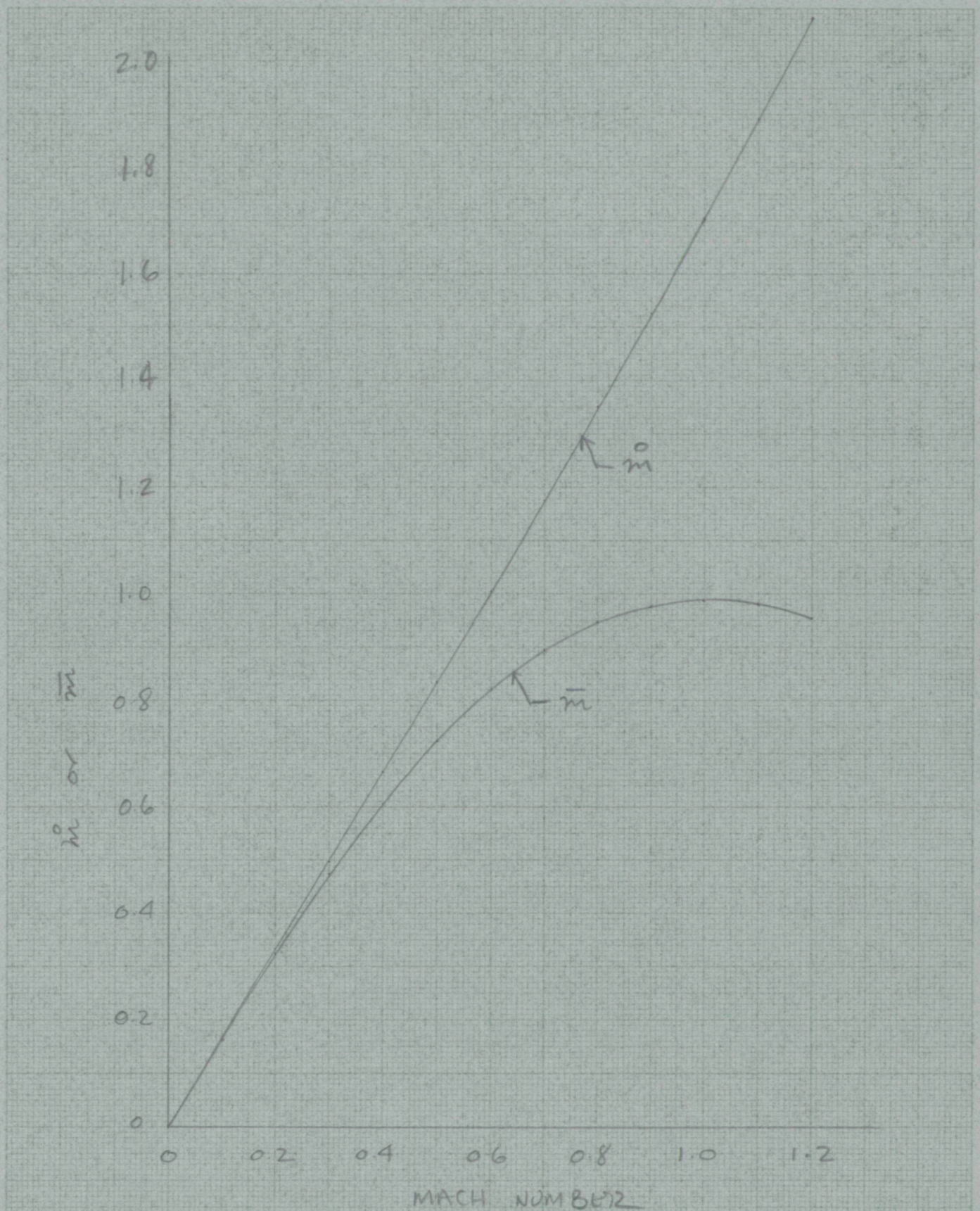

Fig 4. Mass flow functions for Freon, $R = 427 \frac{ft^2}{sec^2 R}$, $\gamma = 1.13$

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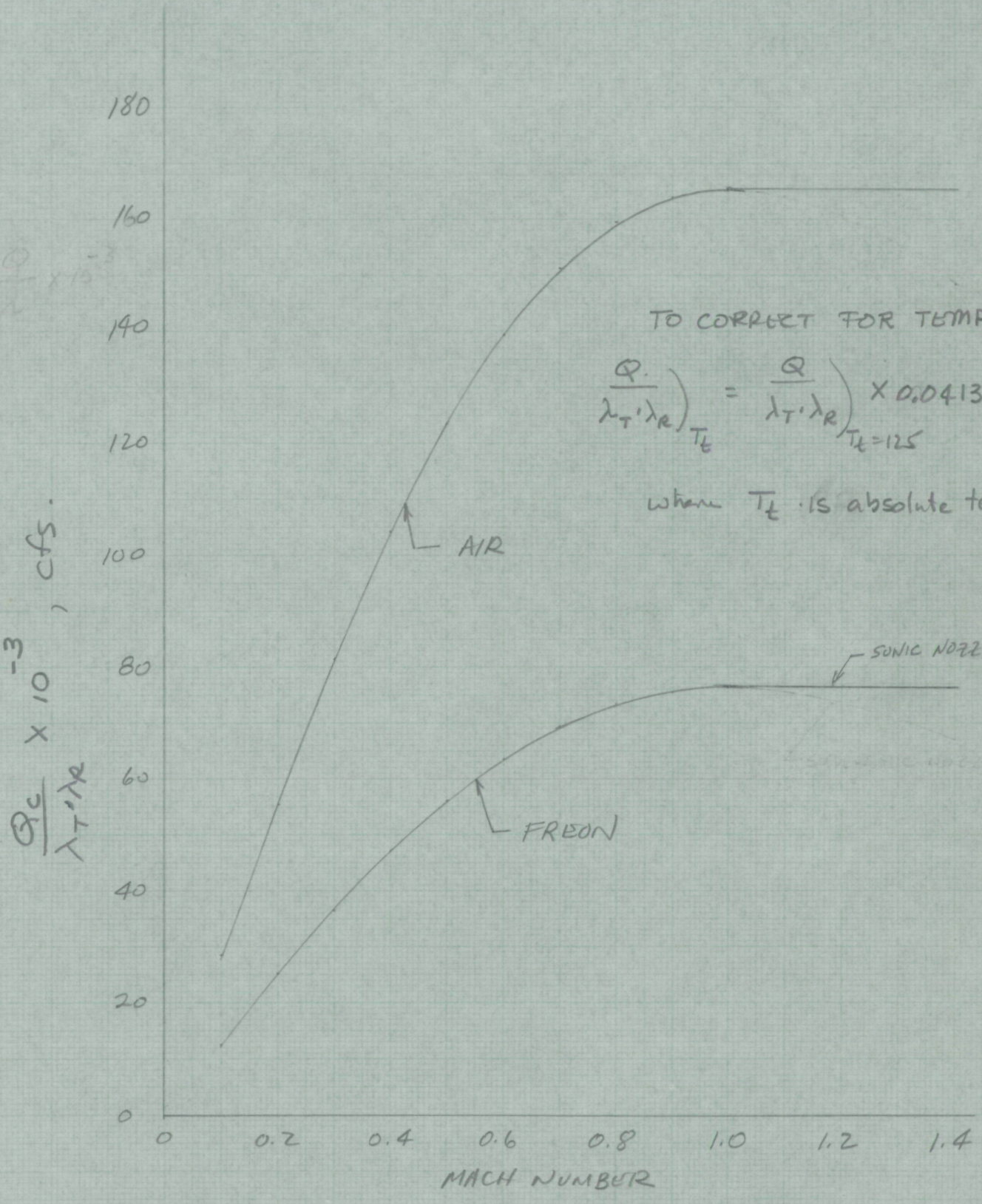

FIG 5 VARIATION OF TUNNEL RESISTANCE WITH MACH NUMBER FOR T_t = 125°F

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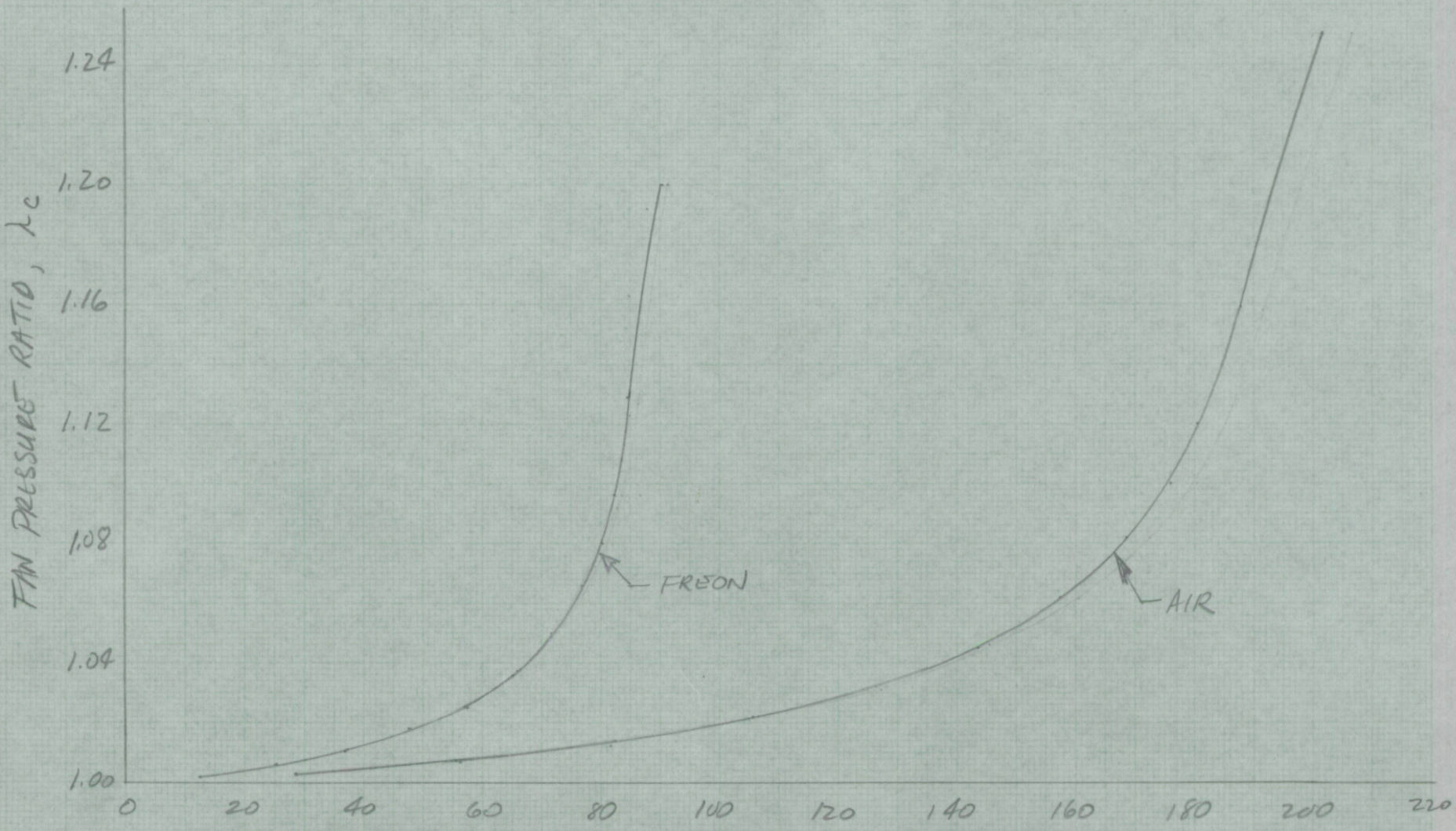

Fig 6. TDT FAN OPERATING CONDITIONS, $T_t = 125°F$.

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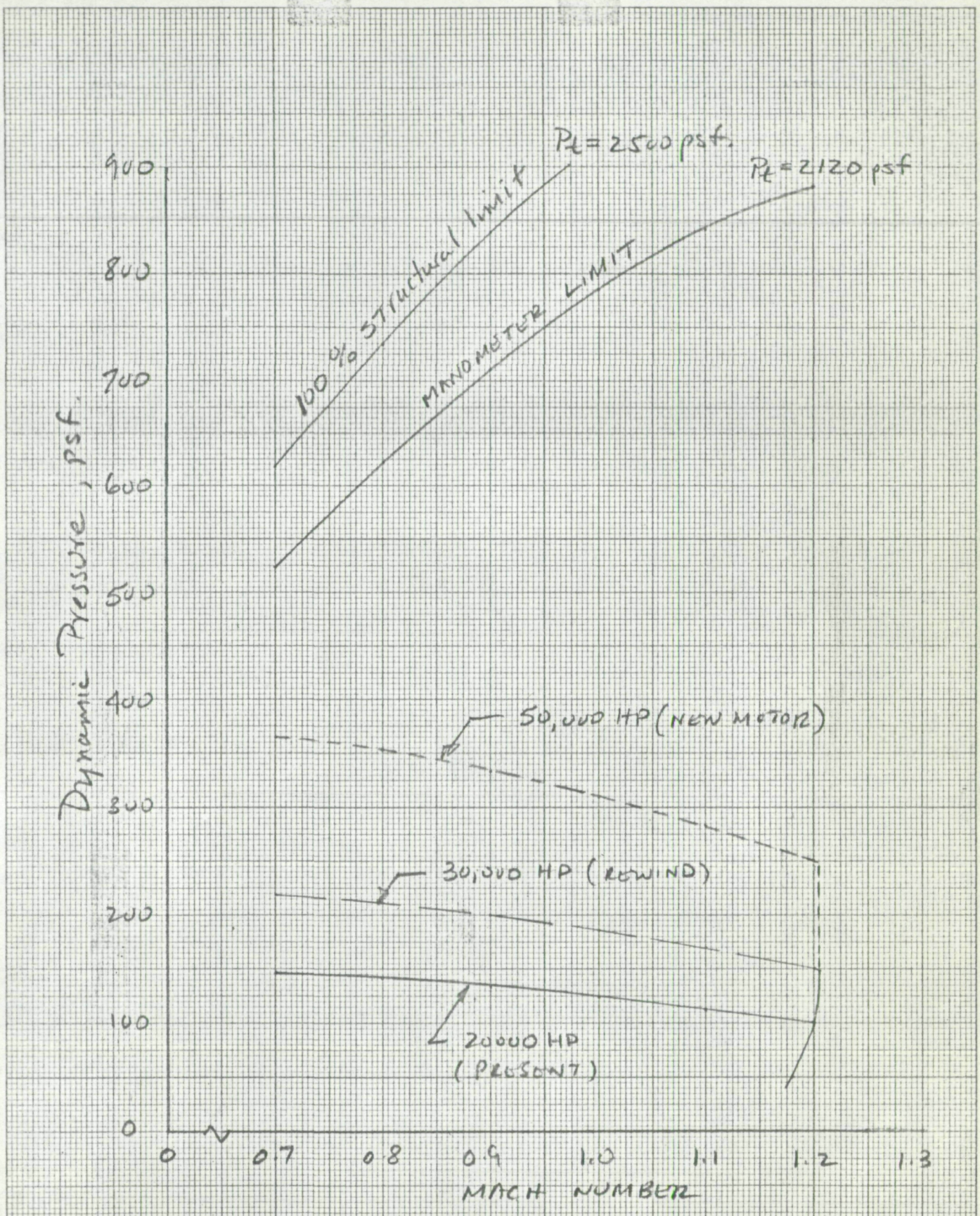

Fig 7. Estimated TDT Performance with Air for Proposed Main Drive Modifications

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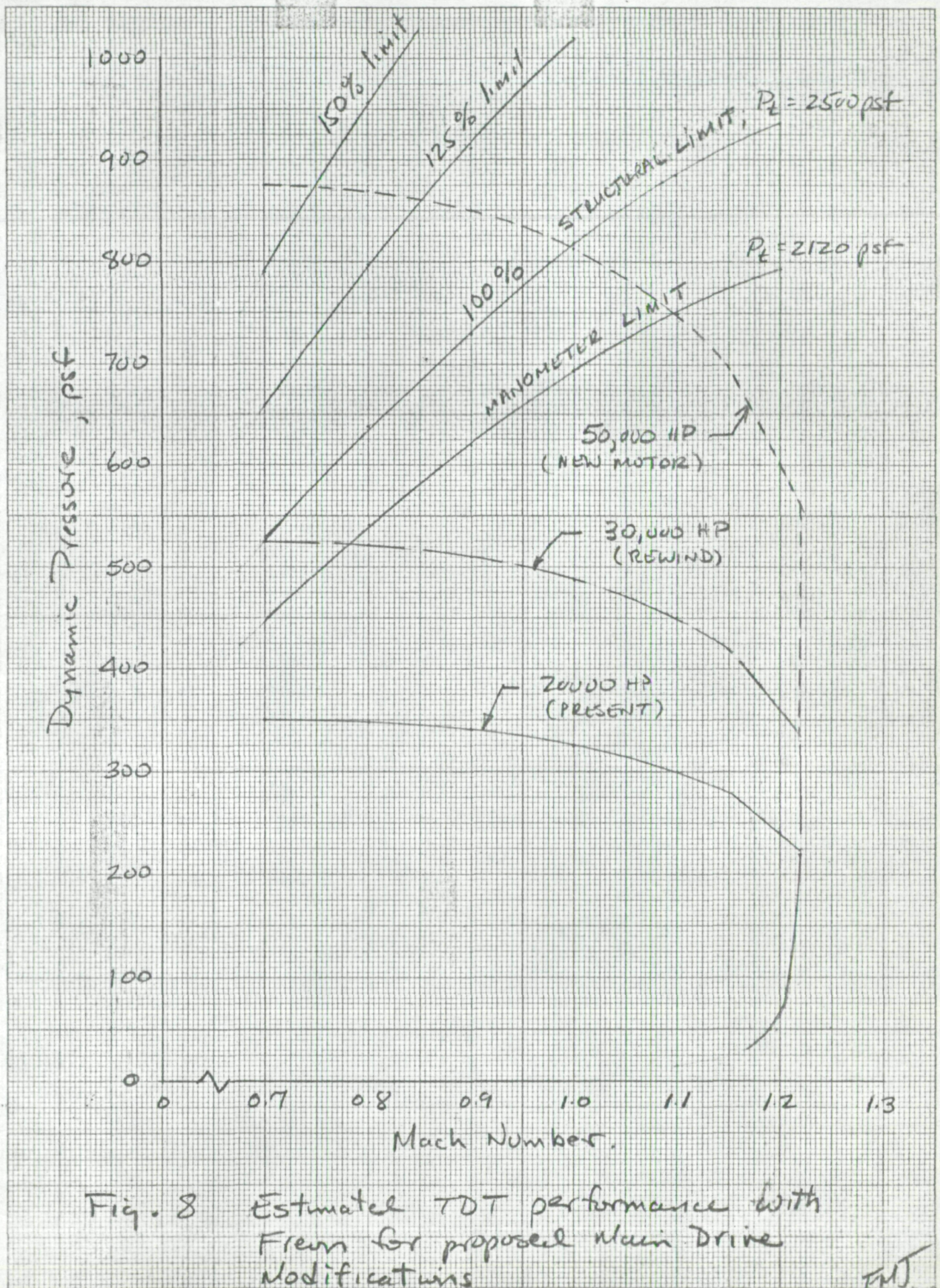

Fig. 8 Estimated TDT performance with Freon for proposed Main Drive Modifications

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JOB LANGLEY TDT STUDY SHEET NO. 1 OF 5

DATE 6/4/73

COMPUTATIONS FOR TDT PERFORMANCE BY FH Jackson CHKD

WITH AN AUXILIARY COMPRESSOR SYSTEMS

Two possible modification alternatives were selected for estimation of performance gains. These included the addition of a 10,000 HP system with the present 20,000 HP main drive and the addition of a 15,000 HP system with the proposed 30,000 HP main drive. Because of the complications and high cost of matching the auxiliary system for operation with both Air and Freon, the auxiliary system was designed for a Freon only operation. Consequently the estimations of performance gains are limited to that for Freon only operation. One would expect that the Freon system would be able to provide some increased performance with Air. The much smaller range for which an improved performance could be obtained would be significantly reduced. For this reason, the evaluation of this modification alternative, should not be based on the performance of the Freon systems with Air. Consequently the performance of the auxiliary systems with Air as a test medium is considered somewhat academic but subject to a detailed study during the final design phase of the systems.

The results of the TDT circuit pressure loss calculations indicated that the

highest tunnel losses were associated with the diffuser flap operation. The losses were found to be associated with the shock losses associated with the high Mach numbers required to pump the plenum flow and with losses attributed to reentry of low energy air into the diffuser. In addition it was assumed that the reentry of the low energy air into the boundry layer at the entrance of the diffuser would initiate diffuser flow separation at $M_{\infty} > 0.7$. The pressure loss of the components affected are presented in Figs 1 and 2. It was concluded, based on these data, that a significant increase in TDT performance could be obtained by replacement of flap suction with an auxiliary compressor system.

The loss coefficients associated with the flap operation are discussed in earlier works. Ref "Tunnel circuit losses" 5-9-73. These results are summarized as follows for freon:

Mach	$\Delta P/q$		
	FLAP LOSS	SHOCK LOSS	DIFFUSER + LOSS
0.8	0	0	0.0437
0.9	.0250	0	↓
1.0	.0550	0.0030	
1.1	.0780	0.0434	
1.2	.0875	0.1665	

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JOB LANGLEY TDT STUDY

SHEET NO. 3 OF 5

DATE 6/4/73

COMPUTATIONS FOR TDT PERF WITH AN AUX. COMP. SYSTEM

BY [illegible] CHKD [illegible]

For purposes of performance gain, it is assumed that the flap and diffuser losses are eliminated and that the shock losses are reduced to the following values.

Mach	SHOCK LOSS, $\Delta P/q$
0.8	0
0.9	0
1.0	0.0003
1.1	0.0325
1.2	0.1043

Introduction of the auxiliary system flow back into the tunnel, if done improperly could provide a total pressure loss. The reentry system however has been designed with the intent that an ejector action and hence a total pressure gain would result. Since this is difficult to guarantee and in an attempt to be conservative it is assumed that at the worse, the reentry of the auxiliary system flow would not cause any pressure loss.

A reduction of the circuit losses result in a decrease in the circuit pressure ratio requirements. It can be shown that for a constant fan volume flow and efficiency (this assumption should produce conservative results)

that the total pressure, and hence the tunnel dynamic pressure, will increase as follows:

$$P_{t_{\infty_{AS}}} = P_{t_{\infty_P}} \cdot \frac{\left(\lambda_c^{\frac{\gamma-1}{\gamma}} - 1.0\right)_P}{\left(\lambda_c^{\frac{\gamma-1}{\gamma}} - 1.0\right)_{AS}} \cdot \frac{\lambda_{c_{AS}}}{\lambda_{c_P}}$$

where AS is for auxiliary system
P, is for the performance of the main drive without auxiliary system.

Then for the indicated loss reductions, the decreases in pressure ratio requirements and the resulting performance improvements were found to be as follows:

MACH	% decrease IN λ_c	% INCREASE IN PRESSURE
0.8	9.2	10.3
0.9	20.7	23.2
1.0	34.2	48.6
1.1	39.8	57.0
1.2	44.9	64.0

Based on these indicated margins of improvement the performance of the TDT with Freon and for the two auxiliary system alternatives was estimated. These data are presented in Fig 3 and summarized

in the following table;

Mach	Dynamic Pressure, q, PSF			
	20,000 HP DRIVE	20,000 HP + AS	30,000 HP DRIVE	30000 HP + AS
0.8	348	384	522	576
0.9	340	419	570	628
1.0	325	482	487	723
1.1	300	471	450	706
1.2	240	394	360	590

The data in Fig 3 indicates that the addition of an auxiliary system provides more performance than an equal amount of power added to the main drive at $M_\infty > 1.0$. For $M_\infty < 1.0$ the performance gain with an auxiliary system is significantly less than that obtained by modifying the main drive.

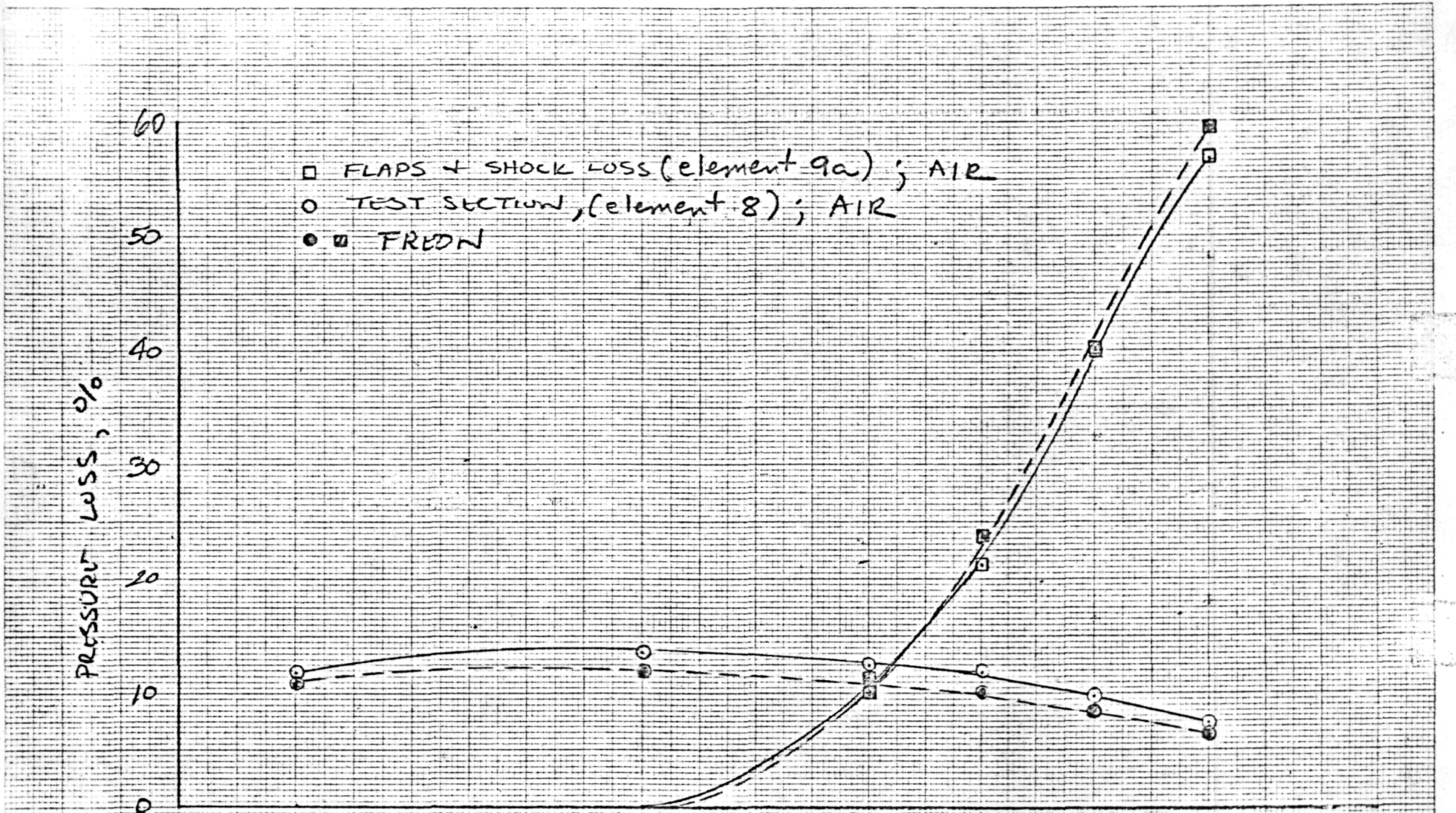

Fig 12 Pressure Loss of the LANGLEY TDT TEST SECTION AND FLAPS at VARIOUS MACH NUMBERS.

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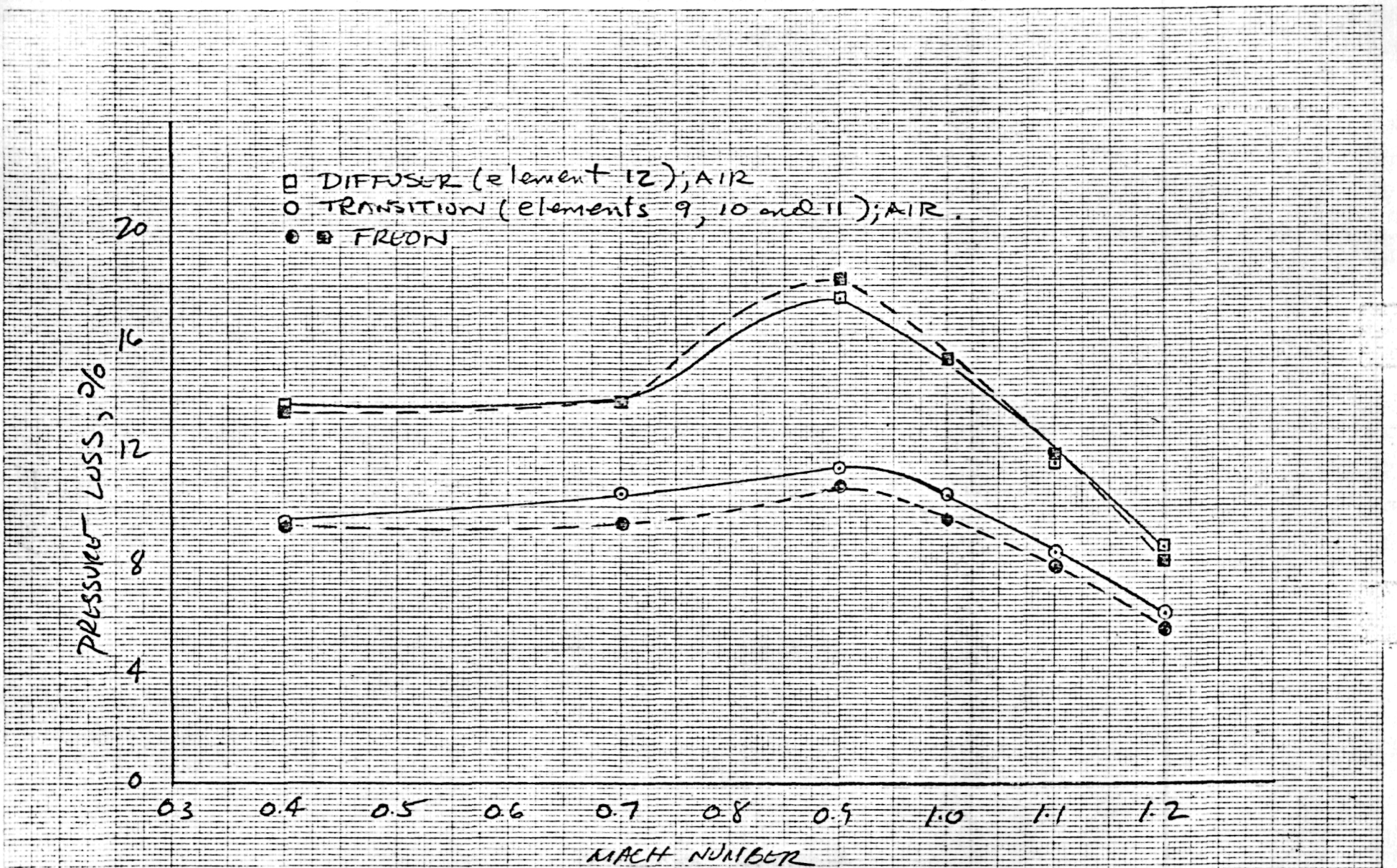

Fig. 2 Pressure Loss of the LANGLEY TDT West Leg Diffuser and Transition at various Mach Numbers.

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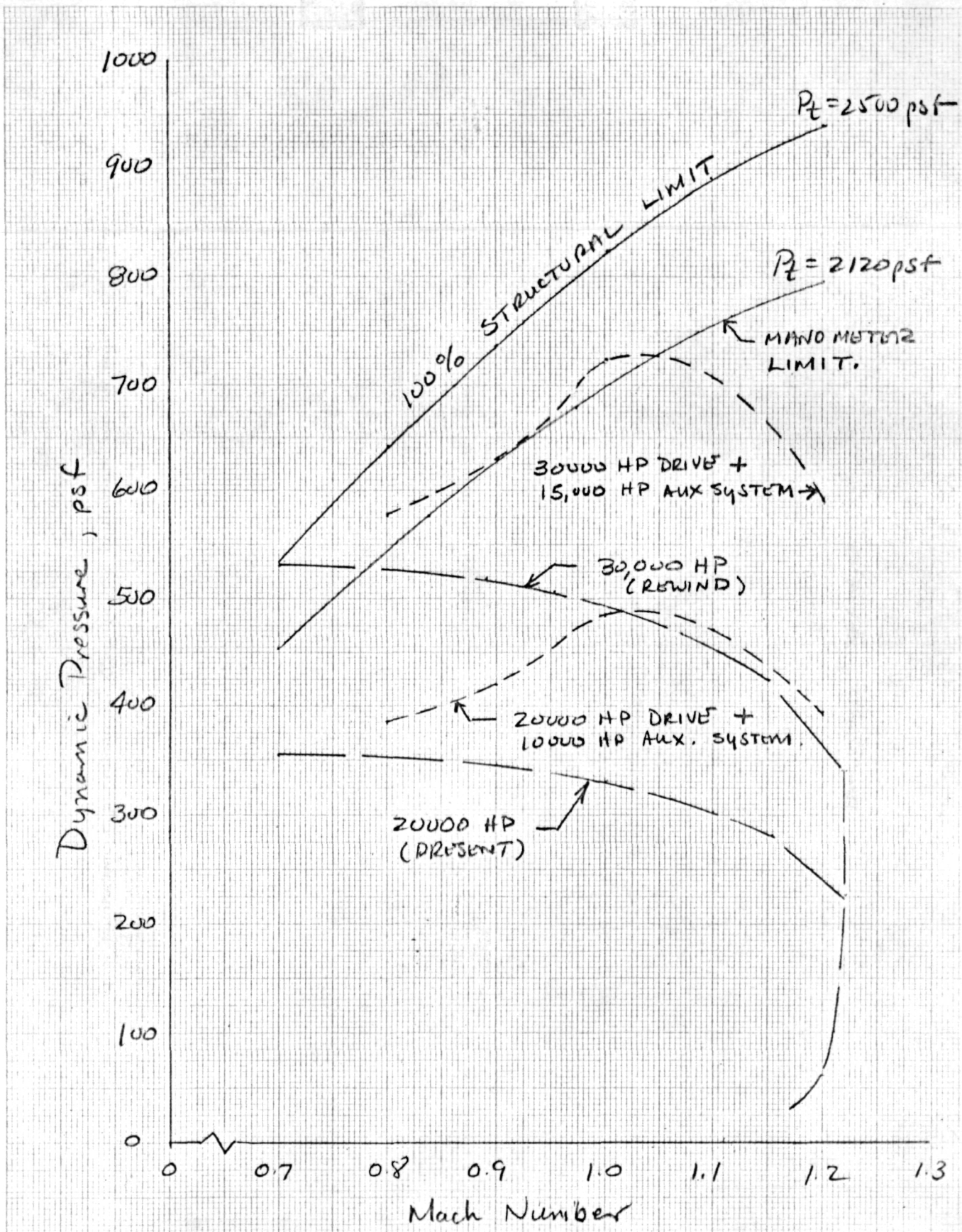

Fig 3 ESTIMATED TDT Performance with Freon for the Addition of 10,000 and 15,000 HP auxiliary compressor systems.

APPENDIX F

AUXILIARY COMPRESSOR SYSTEM

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JOB LANGLEY TDT STUDY SHEET NO. 1 OF 3

COMPUTATIONS FOR AUXILIARY SYSTEM COMPRESSION RATIO (Preliminary Work) DATE 11/17/72

BY [signature] CHKD

The Aux. system Compression ratio may be defined as:

(1) $\lambda_a = P_{exit} / P_{inlet}$

where $P_{EXIT} = K_e P_D$

$P_{inlet} = K_i P_\infty$

where K_e = factor for losses through aftercooler and return ducting.

P_D = pressure in 1st diffuser where air is returned.

K_i = factor for losses through inlet ducting and across test section walls

P_∞ = test section static pressure

so that:

(2) $\lambda_a = K_e P_D / K_i P_\infty$

the pressure ratio across the working section is $\lambda_T = \frac{P_{t_\infty}}{P_D}$

so that:

(3) $\lambda_a = \frac{K_e}{K_i \lambda_T} \cdot \left(\frac{P_t}{P}\right)_\infty$

where $(P_t/P)_\infty = f(M_\infty)$; Test section Mach number.

assume $K_e = 1.08$ and $K_i = 0.90$ for Air

so that:

(4) $\lambda_a = 1.2 (P_t/P)_\infty / \lambda_T$ [AIR]

Now the tunnel pressure ratio, λ_T is dependent upon the magnitude of losses in the test section & 1st Diffuser. Based on the theoretical loss calculation at $M = 0.7$ these losses account for 50% of the tunnel losses. At supersonic Mach numbers these losses will be higher, however, a conservative estimation of λ_a results if we define:

(5) $$\lambda_T = 0.50(\lambda_c - 1) + 1$$

Utilizing the total pressure survey rake data and the plots of Mach vs. RPM & λ_c vs RPM supplied by Abbott, the variation of λ_c with Mach number was defined for AIR as shown in Fig 1.

Now for operation with Freon at the same Mach number & total pressure as with air:

(6) $$q_{FREON} \cong 0.86\, q_{AIR}$$

Because of the higher density of Freon, the ducting Reynolds NO's are higher resulting in lower friction factors and hence loss coefficients, so that:

(7) $$K_{T\,FREON} \cong 0.90\, K_{T\,AIR}$$

This indicates that friction losses (ΔP) are about 22%, and fixed losses about 14% lower for Freon than Air. Then if 30% of the tunnel losses are fixed losses we find:

(8) $$\lambda_{c_{FREON}} \cong 0.80(\lambda_{c_{AIR}} - 1) + 1$$

Based on Eq 8, the variation of λ_c with Mach number was defined for Freon as shown in Fig 1. [Note: From design information the fan was designed for $\lambda = 1.2$ with Freon at 235 RPM ($M \cong 1.2$)]

Then $K_e = 1.064$ and $K_i = 0.92$ for Freon.

so that:

(9) $$\rightarrow \lambda_a = 1.16 \left(P_t/p\right)_\infty / \lambda_T \qquad [\text{FREON}]$$

Utilizing eq.s 4, 5 & 9 the auxiliary system compression ratio requirements were defined as shown in Fig 2.

SUMMARY OF AUXILIARY SYSTEM COMPRESSION RATIO REQD.

FOR THE PRESENT RANGE OF OPERATION ($M_\infty \leq 1.2$)

λ_a; FREON = 2.39

λ_a; AIR = 2.72

FOR EXTENDED OPERATION TO $M_\infty = 1.4$

λ_a; FREON = 3.00

λ_a; AIR = 3.40

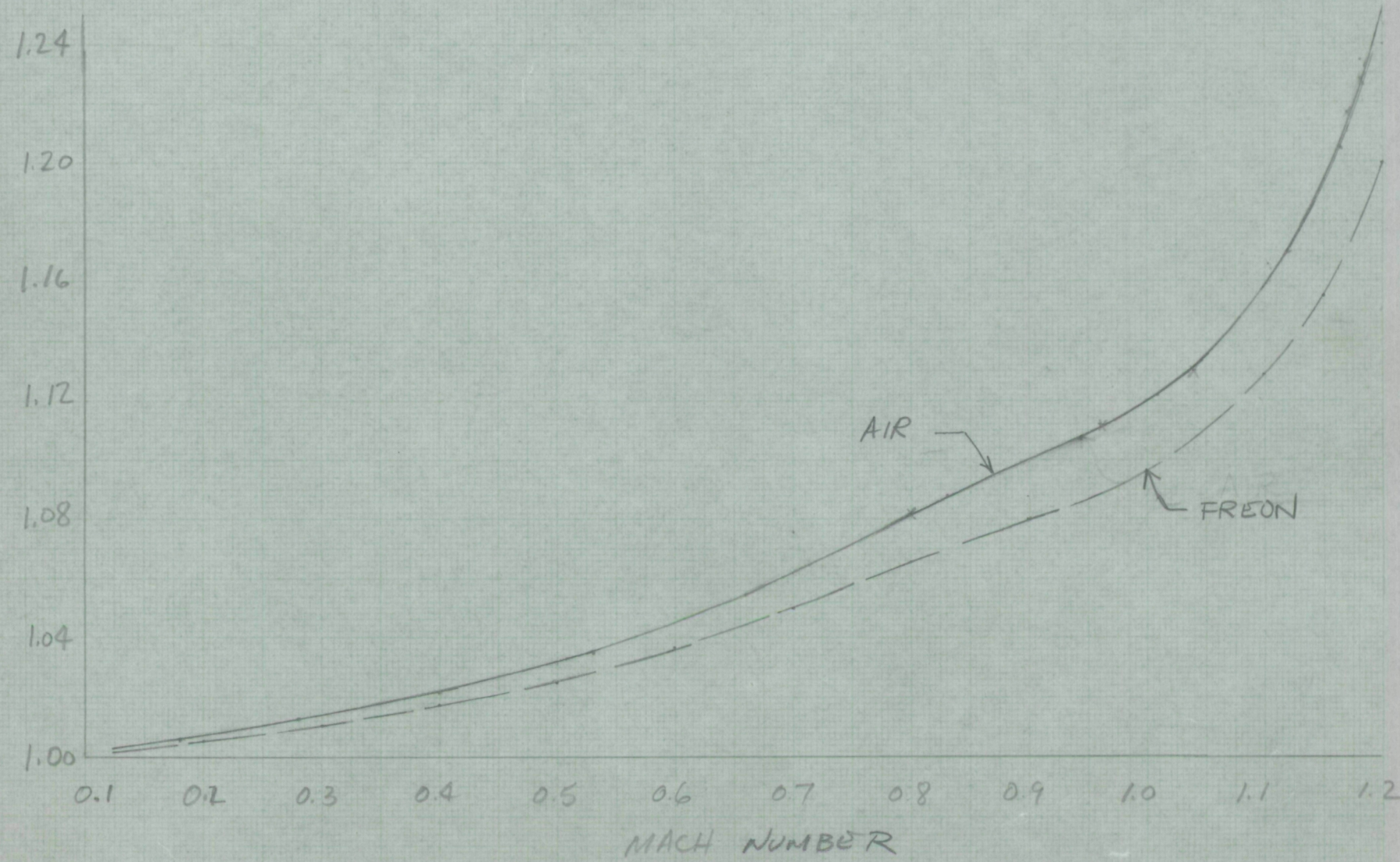

Fig 1. TOT FAN COMPRESSION RATIO.

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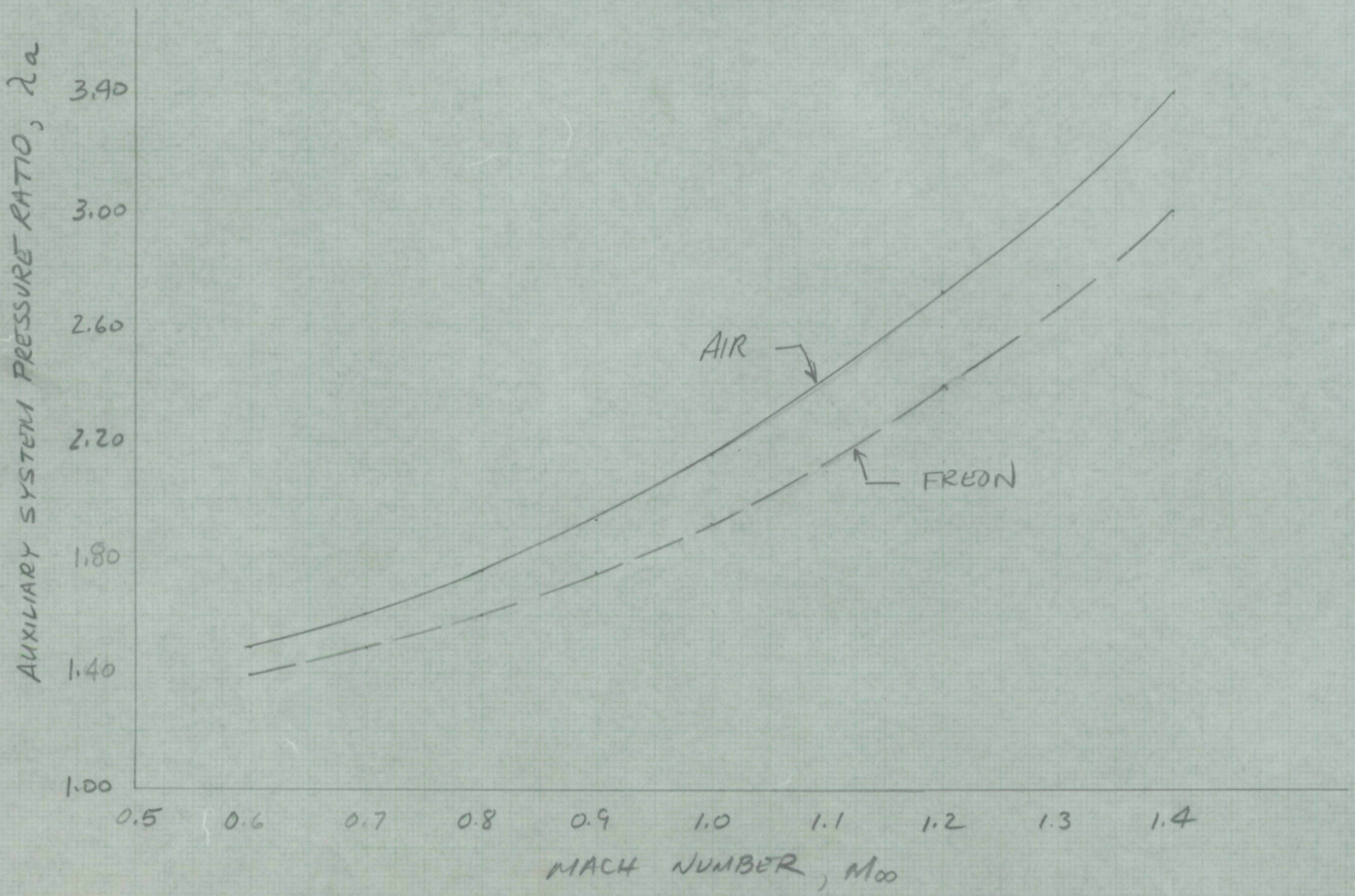

FIG 2. PRESSURE RATIO REQUIREMENTS FOR AUXILIARY SYSTEM FOR PLENUM EVACUATION.

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JOB LANGLEY TDT STUDY SHEET NO. 1 OF 3

COMPUTATIONS FOR Auxiliary System Volume Flow (Prelminary Work) DATE 11/20/72

BY [illegible] CHKD

The Auxiliary System volume flow may be defined as:

(1) $Q_a = W_a R T_a / g P_a$

where W_a is system weight flow ; #/sec

$R = 1716\ FT^2/sec^2\,^oR$ for AIR & $= 427$ for Freon

T_a = aux. compressor inlet temp; ^oR

P_a = aux compressor inlet pressure ; psf.

Assume: $T_a = T_{t_{00}}$

$P_a = P_{00}$ (losses will be considered later)

Then we have for the volume flow:

(2) $Q_a' = \left(\frac{W_a}{W_T}\right) \frac{W_T R T_{t_{00}}}{g P_{00}}$

where $Q_a' = Q_a K_i$; K_i = inlet loss ratio

W_T is tunnel weight flow ; #/sec

Now the tunnel weight flow may be defined as:

(3) $W_T = \dot{m} P_{STA\,45} A_{STA\,45} / \sqrt{T_{t_{00}}}$

where $A_{STA\,45} = 241.08\ FT^2$

(4) $\dot{m} = g\sqrt{\frac{\gamma}{R}} M_{00} \left[1 + \frac{\gamma-1}{2} M_{00}^2\right]^{1/2}$

for AIR, $\gamma = 1.40$ + for Freon, $\gamma = 1.13$

Again for the volume flow we write:

$$(5)\quad Q_a' = \left(\frac{W_a}{W_T}\right)\frac{R}{g}\sqrt{T_{t_\infty}}\,\dot{m}\,A_{45}\,\frac{P_{45}}{P_\infty}$$

For operation @ $M < 1.0$ and for operation with a supersonic nozzle @ $M > 1.0$: $P_{45} = P_\infty$

For Sonic nozzle operation @ $M \geq 1.0$:

$$(6)\quad P_\infty = P_{T_\infty}\left[1 + \frac{\gamma-1}{2}M_\infty^2\right]^{-\gamma/\gamma-1}$$

and

$$(7)\quad P_{45} = P_{T_\infty}\left[\frac{\gamma+1}{2}\right]^{-\gamma/\gamma-1} \quad ; \text{ cond for } M_\infty = 1.0$$

Utlizing equation (5) for $T_{t_\infty} = 125°F$ the auxiliary system volume flow requirements were defined for various W_a/W_T. These results are given in Fig 1 for AIR and Fig 2 for Freon. The data are plotted as a function of λ_a which is related to M_∞ as shown in Fig 3.

Selection of System Volume Flow Requirements:

Ref 1. "Transonic Wind Tunnel Testing", B. H. Goethert

Ref 2. Proceedings of the PWT Transonic Seminar Vol 1, AEDC Preprint, July 1956.

Ref 3. Wind Tunnel Investigations of Transonic Test Sections - Phase III, Edwin Allen AEDC TR-54-53, Feb 1955

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JOB LANGLEY TDT STUDY SHEET NO. 3 OF 3

COMPUTATIONS FOR Auxiliary System Volume Flow DATE 11/20/72

BY HJ Jackson CHKD

Based upon data in the above references. a weight flow ratio, W_a/W_T = 0.05 @ M = 1.2 is selected for a preliminary design point for the auxiliary system. It is possible that slightly less flow removal could be utilized however this is adequate to provide a ballpark cost of the system. In addition a W_a/W_T = 0.05 should be adequate for testing models on the order of about 3% host section blockage. Assuming utilization of a supersonic nozzle @ M = 1.4 this system would provide a W_a/W_T = 0.0422 M = 1.4 which should just be adequate for supersonic operation.

Then from Fig 1 & 2 for W_a/W_T = 0.05

Q_a'; AIR = 20,000 cfs.

Q_a'; FREON = 8,300 cfs.

for the following assumed inlet losses:

K_i FREON = 0.92 & K_i AIR = 0.90

we have:

Q_a; AIR = 22,222 cfs.

Q_a; FREON = 9,022 cfs.

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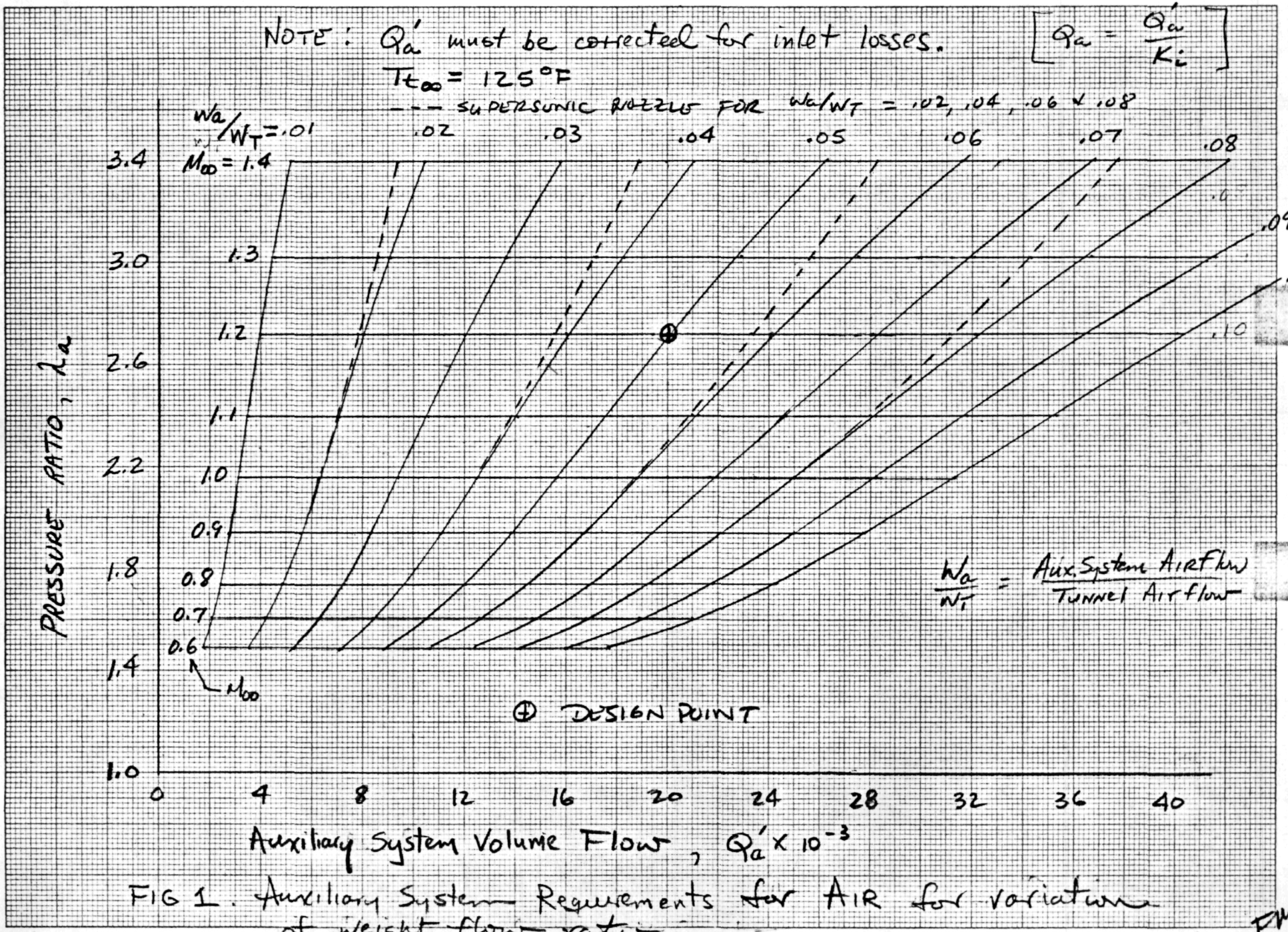

FIG 1. Auxiliary System Requirements for AIR for variation of weight flow ratio.

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? supersonic

Note: Q_a' must be corrected for inlet losses ; $\left[Q_a = \frac{Q_a'}{K_i}\right]$

$T_{t_\infty} = 125\,^\circ F$

--- SUPERSONIC NOZZLE FOR w_a/w_t = .02, .04, .06, .08 & .10

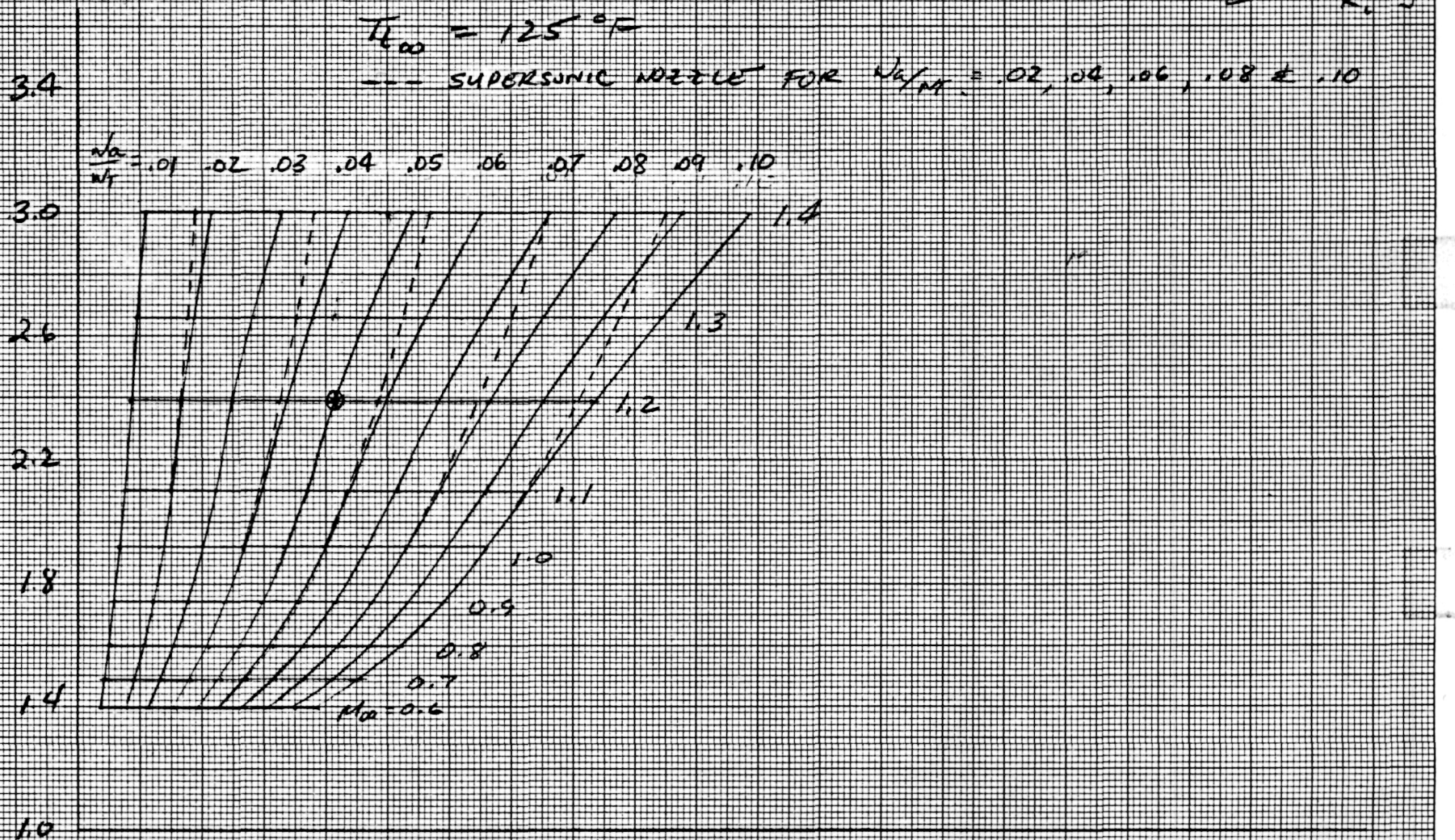

FIG 2. Auxiliary System Requirements for Freon for various weight flow ratios.

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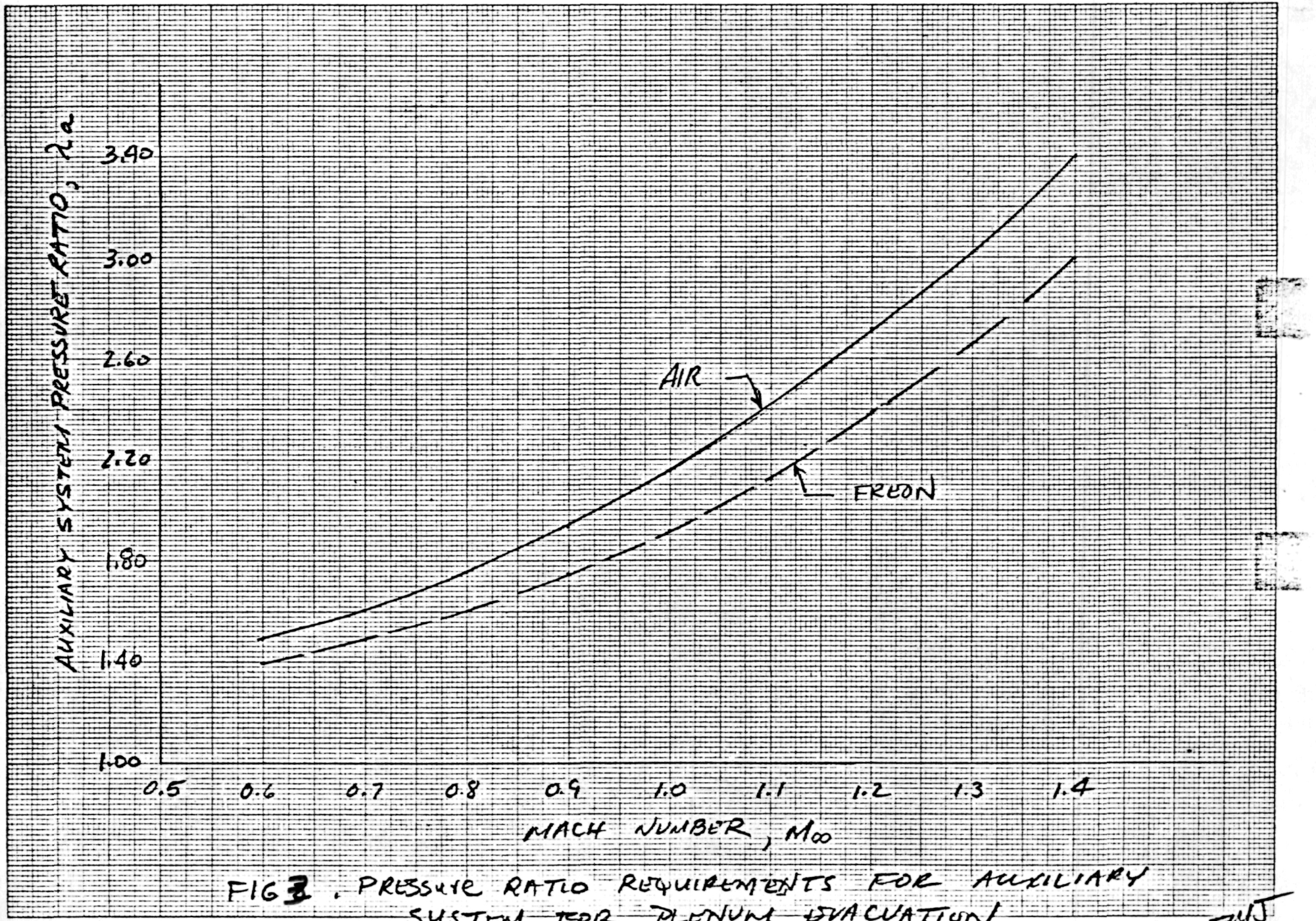

FIG 3. PRESSURE RATIO REQUIREMENTS FOR AUXILIARY SYSTEM FOR PLENUM EVACUATION.

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11/17/1?

The work contained herein either verifies, corrects or replaces previous work on the auxiliary system requirements. Previous work, which is still applicable, is referred to rather than repeated where possible.

I. AUXILIARY SYSTEM VOLUME FLOW.

Ref: "Sink title" 11/20/72 work.

The referenced work derives the proper relationship for the auxiliary system inlet volume flow, ie.

$$(1) \quad Q_a' = \frac{W_a}{W_T} \frac{A_{45} R \sqrt{T_{t\infty}}}{g} \dot{m} \frac{P_{45}}{P_\infty}$$

For the referenced work Q_a' was plotted versus approximated values of λ_a. The auxiliary system compression ratio, λ_a, is a function of the ducting pressure losses. For a constant area and temperature, Q_a' is a function of test section Mach number, M_∞, the ratio of auxiliary weight flow to tunnel weight flow (W_a/W_T) and the test medium. The auxiliary system volume flow requirements for Air and Freon are presented in figs 1 and 2, respectively.

The design point of $W_a/W_T = 0.05$ at $M = 1.2$ is considered valid, especially for the purposes of this study. It would be

recommended that should this modification mode be selected, additional studies be conducted to finalize the auxiliary system flow removal capacity.

At $M_\infty < 1.2$ the indicated auxiliary system will provide significantly more flow removal than the minimum required. A review of the literature indicated that a W_a/W_T of 0.040, 0.0350, 0.0325 and 0.030 would be the minimum required at Mach numbers of 1.1, 1.0, 0.9 and 0.8, respectively. These criteria are noted by the dashed line in Figs 1 and 2.

Finally, it is noted that Q_a' is actually the tunnel plenum chamber volume flow, ie. the auxiliary "system" inlet volume flow. The auxiliary system "compressor" inlet volume flow is found by taking the system inlet ducting pressure recovery into account. ie.

(2) $$Q_a = Q_a'/R_i = \frac{Q_a' P_\infty}{P_{ci}}$$

Therefore to determine the compressor requirements, ie. λ_a and Q_a, we must determine the auxiliary system ducting pressure losses.

II AUXILIARY SYSTEM DUCTING LOSSES

Refs: (1) Auxiliary system Ducting Size; 1/22/73
(2) Aux. System Reentry Flaps; 1/25/73
(3) Review of Preliminary Design for Auxiliary System, 2/6/73.
(4) Duct Losses for Preliminary Auxiliary System Design, 2/15/73
(5) Additional comments on Auxiliary System Layout, 2/24/73.

Refs (1) and (2) were very preliminary in nature but provided insight into the auxiliary system design. The equations and design concepts are valid however, the duct and flap sizes are superseded by later work.

Based on Refs 3, 4 and 5 a final auxiliary system design layout was selected. The final auxiliary system layout is presented in an S&P drawing by R. H Weiter dated February 1973. It should be noted that this final layout contains a few "non-optimized" components such as the location of the safety screen, some of the ducting sizes and the flow splitting component at the end of the 10' duct. Such refinements can be accomplished during the actual design phase should the auxiliary compressor system be installed at the TDT. The S&P layout therefore suffices for the purposes of this study.

The procedures and equations utilized to calculate the ducting losses are essentially the same as those used for the main aircraft ducting. (see 10/17/72 work) The physical characteristics of the auxiliary ducting is presented in Table 1. The element loss coefficients shown in Table 1 were assumed, based on past experience, for the corners (all vaned), the valves, the cooler and the sudden expansion. Friction losses for these components are negligible. For the other components, the loss coefficients include calculation of the skin losses based on system geometry and an estimate of the friction losses.

The inlet ducting is composed of elements 1 to 10. The exit ducting is composed of elements 12 to 30. Losses are also incurred across the reentry flaps. Because these losses are a function of Flap Mach number and the free stream pressure they are not considered as ducting losses, and will be discussed separately.

The duct loss calculations were made for both AIR AND FREON for test section Mach numbers of 0.8, 0.9, 1.0, 1.1 and 1.2, assuming a system inlet temperature of 125°F. The losses which are a function of system volume flow, were calculated for the maximum flow removal requirements shown in Figs 1 and 2. The

additin losses were calculated at M = 1.1 and 1.2 for 20% additional capacity. It was assumed that the auxiliary system inlet pressure is equal to the test section static pressure, ie $P_a = P_{\infty}$. The system inlet pressure used in the calculations was based on an estimate of the improved performance available with the auxiliary system. Ref.: work dated 11/26/72 "Auxiliary System Power Requirements. The variation of the system inlet pressure is shown in Fig 3. It should be noted that selection of the actual operating pressure is not required since the losses are actually a function of the system volume flow.

The auxiliary system losses for each ducting element are defined once we determine the section Mach number. The Mach number can be found by solving for the mass flow function:

$$(3)\quad \left(\dot{m}\frac{P}{P_t}\right) = f(M_{\infty}, \text{Medium}) = \frac{W\sqrt{T_t}}{P_t A}$$

where

$$(4)\quad W = \frac{Q_a' P_{\infty} g}{R T_t}$$

For Air $R = 1716 \frac{ft^2}{sec^2 °R}$, $T_t = 585°R$

For Freon $R = 427 \frac{ft^2}{sec^2 °R}$; $T_t = 585°R$

and

$g = 32.174$

To obtaining the auxiliary system inlet volume flow from fig 1 and 2, we define the following initial conditions for the inlet ducting losses.

Mach	← FREON →			← AIR →		
	Qa', cfs	Poo	W, #/sec	Qa'	Poo, psf.	W, #/sec
0.8	3000	1440	552.9	7200	500	115.4
0.9	3800	1160	564.2	9000	390	112.5
1.0	4700	940	565.6	11000	310	109.3
1.1	5900	750	566.4	14000	240	107.6
1.1	7080	750	679.7	16800	240	129.1
1.2	8300	520	555.9	20000	190	121.8
1.2	9960	520	662.9	24000	190	146.4

An evaluation of the various elements which constitute the inlet ducting is presented in Fig 4. These data are for the design condition of $M_{oo} = 1.2$ and $W_A/W_T = 0.05$. The data in Fig 4 indicate that about one-half of the losses occur in the diverging branch which splits the flow at the end of the 10' duct. A considerable effort was made to improve the loss coefficient for this particular element. These efforts however usually produced designs which would be difficult and expensive to manufacture. It was concluded that it would be difficult to avoid this high loss element and any possible

improvement would be the subject of a detailed analysis which is beyond the scope of this study. Because of these facts and because fig 4 indicates that the losses are otherwise reasonably distributed throughout the system, the inlet ducting design shown in the S+P drawing was considered satisfactory for the purposes of this study.

The results of the inlet ducting loss calculations are presented in figs 5 and 6 for Fuel and Air operation respectively. The inlet ducting pressure recovery for the minimum flow removal requirements at Mach numbers from 0.8 to 1.2 is also shown in figs 5 and 6. The data in figs 5 and 6, indicate that the pressure recoveries are significantly higher than those assumed in earlier work (11/17/72, "Auxiliary System Compression Ratio"). Higher inlet ducting pressure recoveries produces lower system pressure ratio requirements than previously computed.

The auxiliary system exit ducting losses are a function of the overall system losses which determine the auxiliary compressor compression ratio requirements. For specific conditions, therefore, the exit duct losses are determined by an iterative process.

II cont

The exit ducting losses can be shown to be a function of the volume flow at the exit of the ducting, ie the volume flow in the return plenum chamber. The performance of the exit ducting was defined by assuming various initial conditions for the exit ducting.

The compressor exit pressure, P_{ce}, ie, the exit ducting inlet pressure is given by:

(5) $$P_{ce} = P_{oo} \cdot R_i \cdot \lambda_a \quad , psf$$

The values of P_{oo} and, R_i as well as the system weight flow, were defined in the inlet ducting loss analysis for Mach numbers from 0.8 to 1.2. The compression ratio, λ_a, was assumed as previously computed in the work of 11/17/72.

The compressor exit temperature is given by:

(6) $$T_{ce} = T_{ci} \frac{\left(\lambda_a^{\frac{\gamma-1}{\gamma}} - 1\right)}{\eta} + T_{ci} \quad , {}^\circ R$$

Because the compressor efficiency, η must be assumed and because the temperature only has a small effect on the system losses the compressor exit temperature was assumed to be 655°R and 780°R for Freon and Air, respectively. For both Air and Freon the temperature downstream of the aftercooler was assumed to be 585°R.

Based on the above assumptions, the initial conditions used for the exit ducting calculations are as follows:

Mach	Freon			Air		
	Pce	Tce	W/2, #/sec	Pce	Tce	W/2 #/sec
0.8	2290	655	276.4	872	780	57.8
0.9	2011	↓	282.0	750	↓	56.3
1.0	1778		283.0	653		54.6
1.1	1561		283.0	561		53.8
1.1	1544		340.0	553		64.6
1.2	1196		278.0	480		60.6
1.2	1164	↓	331.5	462	↓	73.2

An evaluation of the various elements which constitute the exit ducting is presented in Fig 7. These data are for the assumed conditions at M = 1.2, which approximate the system design conditions. The data in Fig 7 indicate that about 38% of the losses occur in the cooler and the sudden expansion into the reentry plenum, but otherwise the losses are fairly evenly distributed. The high loss associated with the dump into the reentry plenum cannot be avoided. The loss associated with the cooler is subject to the detailed cooler design, hence the exit ducting design was considered acceptable for the purposes of this study.

The results of the exit ducting loss calculations are presented in Figs 8 and 9 for Freon and Air operation respectively. The data in Figs 8 and 9 indicate that the pressure recoveries are higher than those assumed in previous work. It is noted however, that previously the reentry-flap losses were included in the exit pressure loss factor. These reentry flap losses must now be evaluated.

III REENTRY FLAP PERFORMANCE

The recommended design concept for the reentry flaps has been presented in Ref 2. The losses across the reentry flaps are a function of the desired flap exit Mach number and the free stream static pressure.

Ideally it is desired to have a flap exit Mach number higher than the circuit Mach number at the reentry station so that an ejector action is obtained. The static pressure at the exit of the flaps will be equal to the free stream static pressure. The auxiliary system compressors must then provide a sufficient total pressure in the reentry plenum to obtain the desired flap Mach number. The pressure ratio requirements for the reentry flaps at various exit Mach numbers is presented in Fig. 10.

The auxiliary system will exhaust into the tunnel at station 129. The auxiliary system exit conditions then must match the static pressure at sta 129. The velocity of the main stream at sta 129 is sufficiently high enough so that it must be considered. i.e.

(7) $$P_{129} = \frac{P_{t129}}{P_{t\infty}} \cdot \left(\frac{P}{P_t}\right)_{M_{129}} \cdot P_{t\infty}$$

Then the total pressure ratio for the auxiliary system is:

(8) $$\lambda_{AS} = \frac{P_{129}}{P_\infty}$$

From the aircraft loss calculations we obtain the following data:

Medium	M_∞	$P_{t129}/P_{t\infty}$	M_{129}	$(P/P_t)_{129}$	$P_{129}/P_{t\infty}$	λ'_T	P_{129}/P_∞
Air	0.4	0.9946	0.29	0.9433	0.9382	1.066	1.048
	0.7	0.9860	0.46	0.8650	0.8529	1.172	1.183
	0.9	0.9694	0.52	0.8317	0.8062	1.240	1.363
	1.0	0.9539	0.53	0.8259	0.7878	1.269	1.491
	1.1	0.9167	0.56	0.8082	0.7409	1.350	1.582
↓	1.2	0.8570	0.59	0.7901	0.6771	1.477	1.642
Freon	0.4	0.9960	0.29	0.9545	0.9507	1.052	1.039
	0.7	0.9906	0.46	0.8870	0.8787	1.138	1.158
	0.9	0.9781	0.53	0.8520	0.8333	1.200	1.304
	1.0	0.9630	0.54	0.8475	0.8161	1.225	1.412
	1.1	0.9369	0.55	0.8425	0.7916	1.263	1.528
↓	1.2	0.8830	0.57	0.8315	0.7342	1.362	1.603

Note $\lambda'_T = P_{t\infty}/P_{129}$

III cont

The variation of the pressure ratio requirements for the auxiliary system is presented in Fig 11. It is noted that λ_{AS} is the pressure ratio of the total system, not the auxiliary compressor compression ratio. The auxiliary compressor system must also overcome the ducting and flap losses.

The flap exit Mach number which can be obtained is dependent upon the exit flap area. The exit flap area may be written as:

$$(9) \qquad A_f = \frac{W\sqrt{T_t}}{\dot{m}\, P_{129}}$$

where

$$(10) \qquad \dot{m} = f(M_f) = g\sqrt{\frac{\gamma}{R}}\, M_f \left[1 + \frac{\gamma-1}{2} M_f^2\right]^{1/2}$$

The circuit loss data indicate that at the auxiliary system design conditions of Mach 1.20, the Mach number at station 129 is 0.59 and 0.57 for Air and Freon respectively. The data in Fig 10, indicate that an increase in the exit flap Mach number significantly increases the reentry flap pressure ratio, and hence the auxiliary system compression ratio requirements.

III cont.

Consequently, a trade off between the auxiliary system cost and the benefits of ejector action is in order. A brief analysis indicates that for a test section Mach number of 1.2, the reentry of the plenum flow at high Mach numbers adds to the momentum of the main stream. Accordingly, the ejector action provides a negative loss coefficient, ie a total pressure gain. The results indicate mainstream loss coefficients of -0.0356, -0.0704 and -0.1164 for $M_f = 0.6$, 0.8 and 1.0 respectively. These coefficients would produce decreases in the total pressure losses for the TDT circuit of 2.9, 5.7 and 9.5% respectively. The theory assumes perfect mixing of the flows. Perfect mixing however is not believed to occur because of the large size of the TDT diffuser and the small amount of flow through the reentry flaps. Imperfect mixing could negate the ejector action, especially in view of the fact that the area of the main duct is increasing at the reentry station. In view of this and considering that for $M_f = 0.8$ and 1.0, the auxiliary system compressor pressure ratio will be increased by 20 and 50%, it is recommended that an exit flow Mach number of 0.6 be utilized at $M_\infty = 1.2$.

For $M_f = 0.6$ and for the flow conditions corresponding to the design point of $M_\infty = 1.2$ and $W_A/W_T = 0.05$, the total flap area was determined to be 16.46 ft² for Freon and 16.06 ft² for Air. For a twelve flap system, each flap would have an area of about 1.35 ft² for both Air and Freon. Ideally the exit flap mach number for off design conditions, i.e. for $M_\infty < 1.2$, should be at least somewhat larger than the freestream Mach number at station 129. This of course requires that the area of the flaps be variable. For example for $M_\infty = 0.8$ a total flap area of about 9.1 ft² would be required for $M_f = 0.50$. A brief analysis indicates that the loss coefficients at $M_\infty = 0.8$ would be -0.0118 and -0.0388 for flap areas of 16.46 and 9.1 ft², respectively. These coefficients would reduce the pressure loss of the TDT circuit by 2.6 and 8.6%, respectively.

Because of the high cost of a variable reentry flap and considering the previous discussion involving the effectiveness of the ejector action, a constant flap area of about 1.35 ft² is recommended for this preliminary design of the auxiliary system. A fixed flap system would provide flap exit Mach numbers of 0.44, 0.38, 0.34 and 0.29 at $M_\infty = 1.1$, 1.0, 0.9 and 0.8 respectively.

III cont

As previously indicated, the conditions at the reentry flaps determine the losses through the auxiliary system exit ducting (see figs 8 and 9). The reentry plenum volume flow may be defined as.

$$(11) \quad Q_{rp} = Q_f = \left(\dot{m}\frac{P}{P_t}\right)_f A_f \frac{R}{g}\sqrt{T_t}$$

Solving equation 11 for the recommended flap area and the resulting flap Mach numbers, we obtain the variations of reentry plenum volume flow as shown in Fig. 12. The losses for the auxiliary system exit ducting can be obtained from figs 8 and 9. Sufficient data now exist to define the auxiliary system compressor pressure ratio, λ_a, requirements.

IV AUXILIARY SYSTEM COMPRESSOR REQUIREMENTS

Ref: (1) AUXILIARY System Compression Ratio (11/17/72)
(2) AUXILIARY System VOLUME FLOW (11/20/72)

The auxiliary system compressor requirements are defined by the volumetric capacity and the compression ratio. The auxiliary system volume flow has been discussed in Section I and shown to be a function of the inlet ducting losses. Preliminary work on the compression ratio requirements is presented in Ref 1.

Ref 1 presented a correct relationship for the auxiliary system pressure ratio. The estimates for the auxiliary system compression ratio were based on assumed values for the system ducting losses and the tunnel pressure ratio. The equation for the pressure ratio is revised to agree with the nomenclature and the breakdown of losses as presented in this work. Accordingly we have:

$$(12) \qquad \lambda_a = \frac{P_{ce}}{P_{ci}} = \frac{\lambda_{AS} \cdot \lambda_f}{R_i \cdot R_e}$$

where:

λ_{AS} is the total system pressure ratio and is obtained from Fig 11.

λ_f is the reentry flap pressure ratio and is obtained from Fig 10.

R_i is the inlet ducting recovery and is obtained from Figs 5 and 6.

R_e is the exit ducting recovery and is obtained from Figs 8, 9 and 12.

IV cont

Obtaining the data as indicated the auxiliary system compression ratio requirements were defined. These data are presented in Fig 13 for the Mach number range from 0.8 to 1.2. The data in Fig 13 indicate that compressor pressure ratios of 2.43 and 2.18 are required at the design conditions for Air and Freon respectively. Assuming a 20 percent stall margin the auxiliary system should be designed to deliver pressure ratios of 2.72 for Air and 2.42 for Freon. These data indicate that if the auxiliary system is to be used for $N_{/\theta} = 1.2$ for both air and Freon that either a different number of stages of compression are involved or more logically the compressor would have to be operated at different speeds for the two test medium. Although this is possible it would complicate and increase the cost of the auxiliary system.

The auxiliary system inlet volume flow requirements are presented in Figs 1 and 2. It is noted that the compressor volume flow requirements are defined by:

$$Q_a = Q_a' / R_i$$

where the inlet ducting losses are obtained from Figs 5 and 6.

Then by correcting the inlet volume flows required for the minimum flow removal capacities for inlet losses, the following compressor system volume flows are obtained.

Mach	FREON Qa, cfs	AIR Qa cfs.
0.8	3018	7265
0.9	3834	9128
1.0	4769	11230
1.1	6101	14478
1.2	8709	21494

It has been assumed in earlier work that the compressor would be driven by synchronous motors. Then for a fixed compressor speed the machine inlet volume flow is a constant. Accordingly, the auxiliary system was designed to include a two compressor system for Freon operation. Although the available space is critical it appeared that a four compressor system for operation with Air could be installed. The above data indicate that each compressor would have to provide 4355 cfs and 5374 cfs for Freon and Air operation respectively. Considering the fact that some margin should be designed into the system, it appears that matching of the system for both Air and Freon operation is possible.

IV cont

Whether this be done by going to variable speed or different surge compressors or some other plant configuration would be the subject of a detailed analysis. Such an analysis would only be justified should the auxiliary compressor system option be selected for implementation at the TDT. Because of the higher cost of a system capable of operating in both Air and Freon and because about 90% of the testing in the TDT is done with Freon, it is recommended that the Auxiliary system be designed initially for Freon operation. For such a system and assuming a 20% capacity margin, two 5200 cfs compressors would be required. This volumetric capacity can be supplied by any of several compressor manufacturers. Now that the compressor requirements have been defined the power requirements for the auxiliary system can be estimated.

V AUXILIARY SYSTEM POWER REQUIREMENTS.

Ref. 11/26/72 "Same Title".

The referenced work derived the proper relationships for the auxiliary system horsepower requirements; ie.

$$(13) \quad \frac{HP\,\eta_a}{P_{ci}} = \frac{\gamma}{(\gamma-1)\,550}\, Q_a \left(\lambda_a^{\frac{\gamma-1}{\gamma}} - 1\right)$$

Utilizing eq 13 and $\gamma = 1.13$ for Freon, solutions to the horsepower function were obtained as shown in Fig 14. To obtain an estimate for the auxiliary system power requirements, the compressor inlet pressure (P_{ci}), efficiency (η_a), volume flow (Q_a) and pressure ratio, (λ_a) must be known. The pressure ratio requirements have been presented in Fig 13. The volume flow requirements have been defined in section IV. It was recommended that the Freon system consist of two 5200 cfs axial flow compressor. Bypass lines have been included in the system design to allow volume flow matching at each Mach number. The system power is based on the machine inlet volume flow rather than the requirements at each Mach number. The efficiency of the auxiliary compressor system is assumed as shown in Fig 15.

Utilizing Figs 13, 14 and 15, the horsepower/psf, ie. HP/P_{ci}, was defined for the one and two compressor configuration performance as shown in Fig 16. Also shown in Fig 16 are the system operating points. The data in Fig 16 indicate that one compressor would be utilized for operation at $M_\infty \leq 1.05$ and that two compressors would be utilized at $M_\infty > 1.05$.

V cont.

The auxiliary compressor inlet pressure must be known before the actual horsepower requirements can be defined. The compressor inlet pressure is dependent upon the magnitude of improvement provided by the auxiliary system. Consequently an estimation of the performance improvement provided by the auxiliary system is required. This work has been accomplished in other work. (Ref: TDT performance with an auxiliary system). Utilization of an auxiliary system will reduce the circuit losses and therefore reduce the circuit pressure ratio requirements. A reduction in pressure ratio will provide an increase in performance with the present 20,000 HP drive system. The results of the performance improvement with the auxiliary system are summarized as follows:

Mach	% decrease in λ_c	% increase in P_{00}
0.8	10.0	10.3
0.9	20.7	23.2
1.0	34.2	48.6
1.1	39.8	57.0
1.2	44.9	64.0

The variation of P_{00} for various margins of improved tunnel performance is shown in Fig 17. For the indicated margins of improvement and taking into consideration the inlet ducting losses from Fig 5, the compressor

inlet pressures which would exist for utilization of an auxiliary system with a 20,000 and 30000 HP main drive were estimated. These data are shown in Fig 18. The data at $M_{100} = 0.9$ was increased slightly to provide a smooth curve. Utilizing the data in Figs 16 and 18, the power requirements of an auxiliary system with the two main drive powers was determined as shown in Fig 19. The data in Fig 19 indicate that each compressor should be powered for 5200 HP with the 20,000 HP drive and 7800 HP with the 30,000 HP drive. Although the total system powers are 10400 and 15600 HP the two auxiliary systems will be referred to as the 10,000 and 15,000 HP systems. It has been assumed that the auxiliary system compressors will be capable of about the same overload capability as the main drive motor. Should this not be so, the auxiliary system inlet valves could probably be throttled to hold the auxiliary system power within limits.

SVERDRUP & PARCEL

JOB LANGLEY TDT STUDY

SHEET NO. OF

DATE 5/28/73

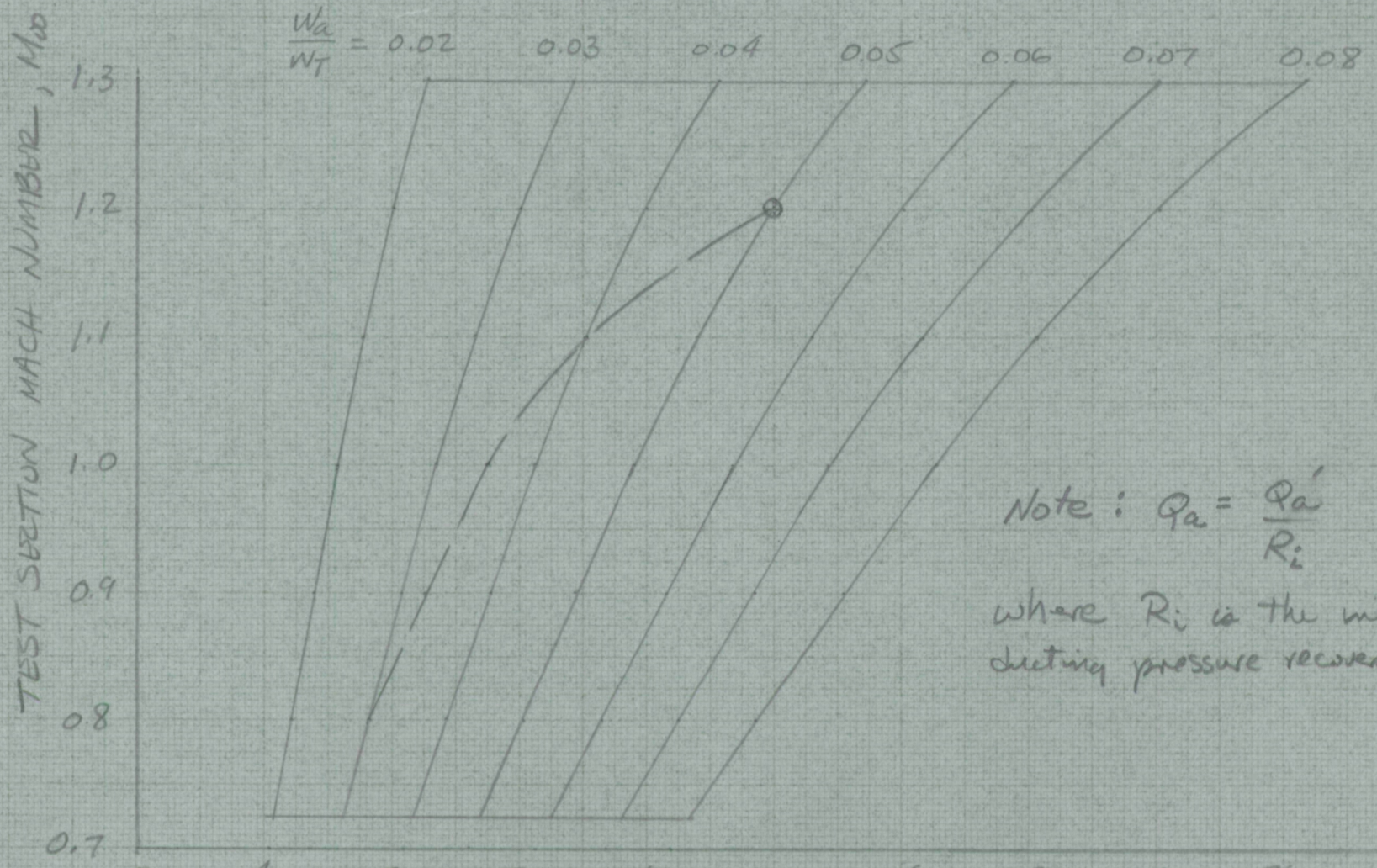
COMPUTATIONS FOR

BY CHKD

TABLE 1

AUXILIARY SYSTEM DUCTING CHARACTERISTICS

element	Type loss	Area, ft^2	Diam., ft	L, ft.	2θ°	Loss Coeff.
1	contraction	262.47	18.29	10	45	0.05
2	90° Corner	78.54	10.00			0.15
3	PIPE	78.54	10.00	100		
4	90° corner	78.54	10.00			0.15
5	Diverging Branch	78.54	10.00			1.00
6	PIPE	44.18	7.50	28		
7	90° corner	44.18	7.50			0.15
8	valve	44.18	7.50			0.25
9	Screen	44.18	7.50	B=80%		0.25
10	expansion	44.18	7.50	10		0.04
11	Comp. INLET	63.00	D_H = 8.96			
12	expan + resist	23.76	5.50	3	45.2	0.16
13	cooler	50.26	8.00			3.00
14	contractin	50.26	8.00	3	45.2	0.001
15	valve	23.76	5.50			0.25
16	90° corner	23.76	5.50			0.15
17	60° corner	23.76	5.50			0.15
18	Conv. Branch	23.76	5.50			0.36
19	pipe	44.18	7.50	35		
20	90° corner	44.18	7.50			0.15
21	PIPE	44.18	7.50	110		
22	90° corner	44.18	7.50			0.15
23	PIPE	44.18	7.50	40		
24	90° corner	44.18	7.50			0.15
25	PIPE	44.18	7.50	130		
26	30° corner	44.18	7.50			0.15
27	PIPE	44.18	7.50	45		
28	90° corner	44.18	7.50			0.15
29	expansion	44.18	7.50	9	5.5	0.015
30	sudden expan.	~55.00	D_H = 8.37			1.00
31	REENTRY PLENUM	~500.0				



Note: $Q_a = \frac{Q_a'}{R_i}$

where R_i is the inlet ducting pressure recovery, $\frac{P_{ci}}{P_\infty}$

Fig 1 Auxiliary System Volume Flow Requriements for AIR; $T_t = 125°F$

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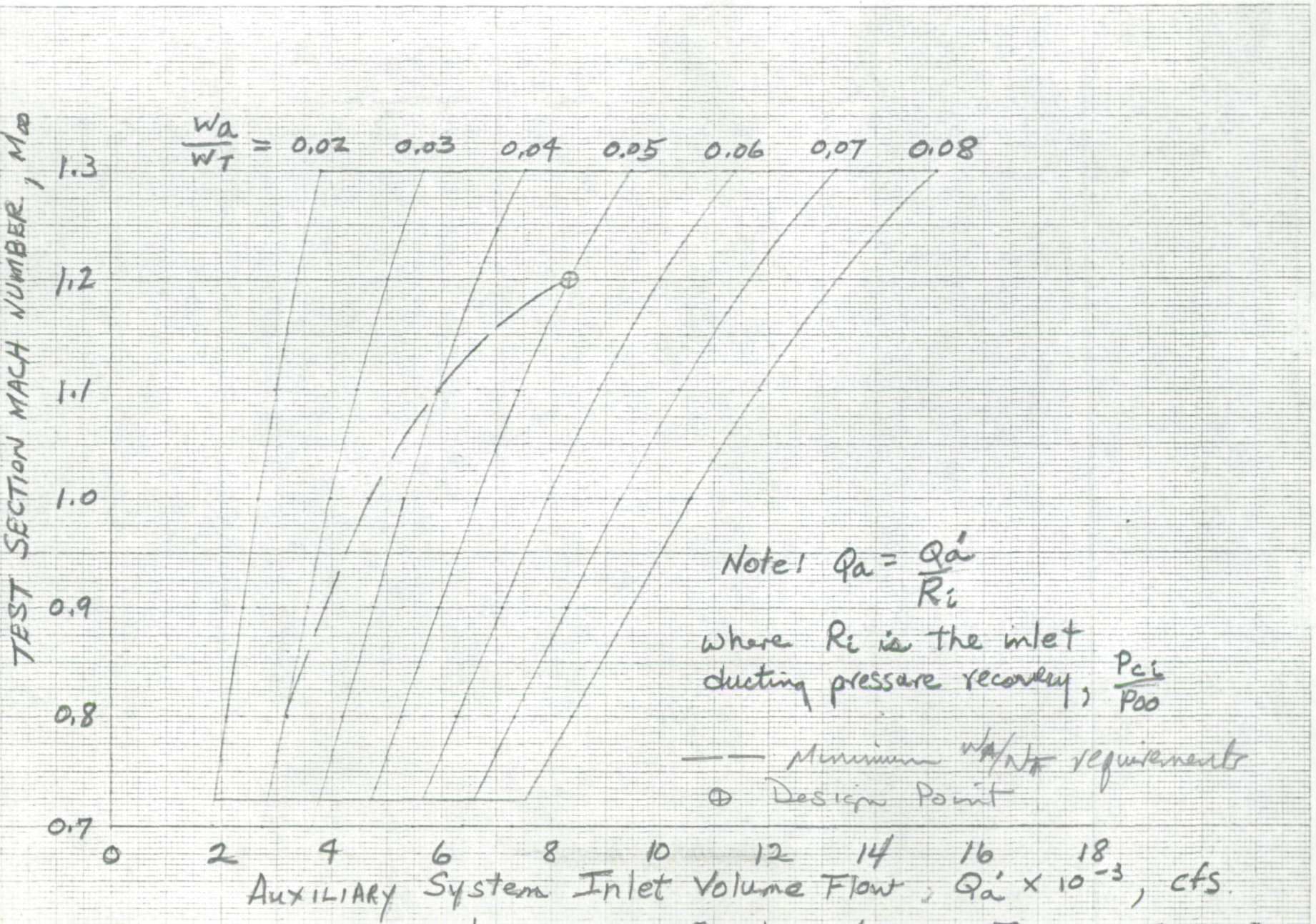

Fig 2. Auxiliary System Volume Flow Requirements for FREON; $T_t = 125°F$.

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F.J.

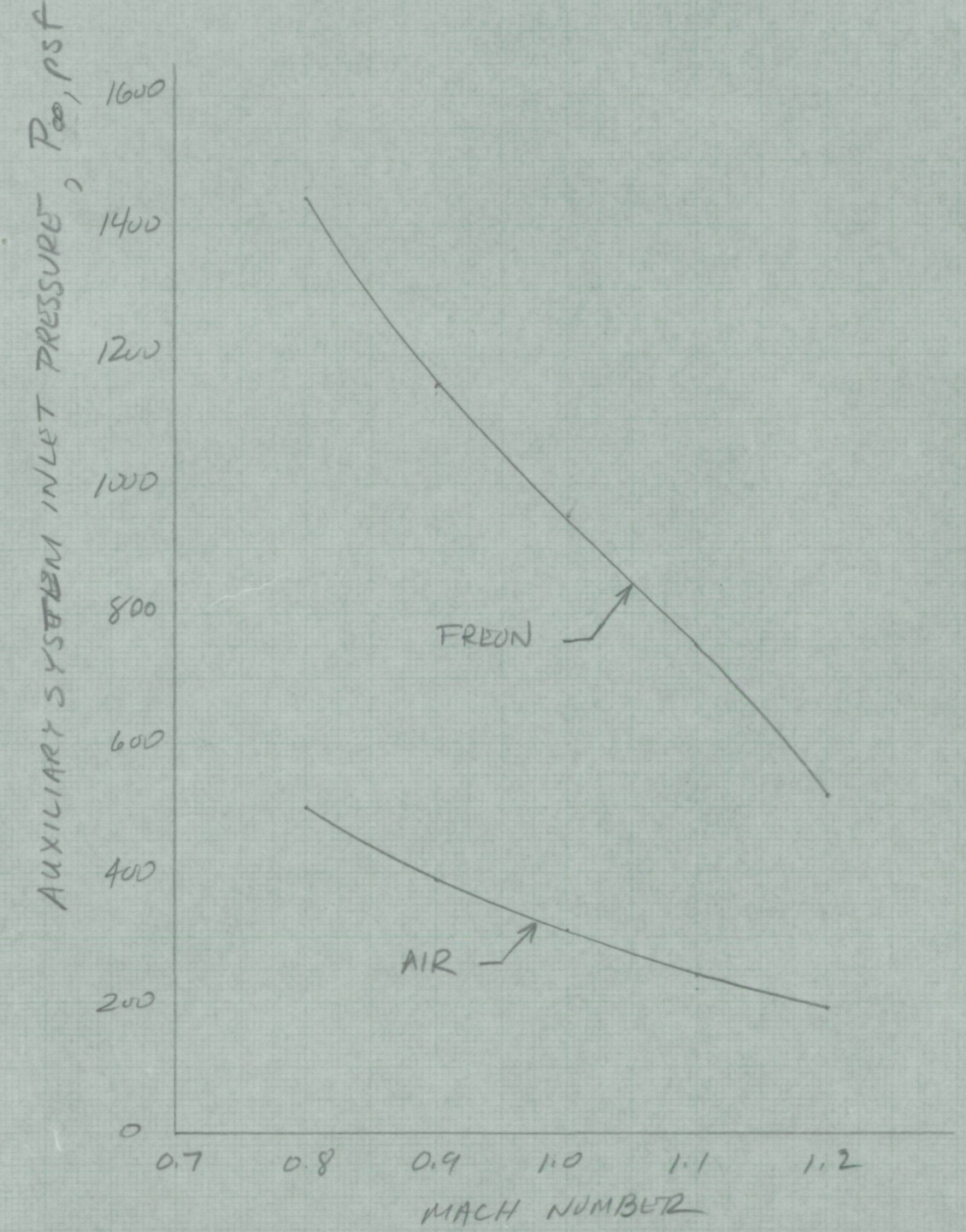

FIG 31. ESTIMATED INLET PRESSURE FOR THE AUXILIARY COMPRESSOR SYSTEM.

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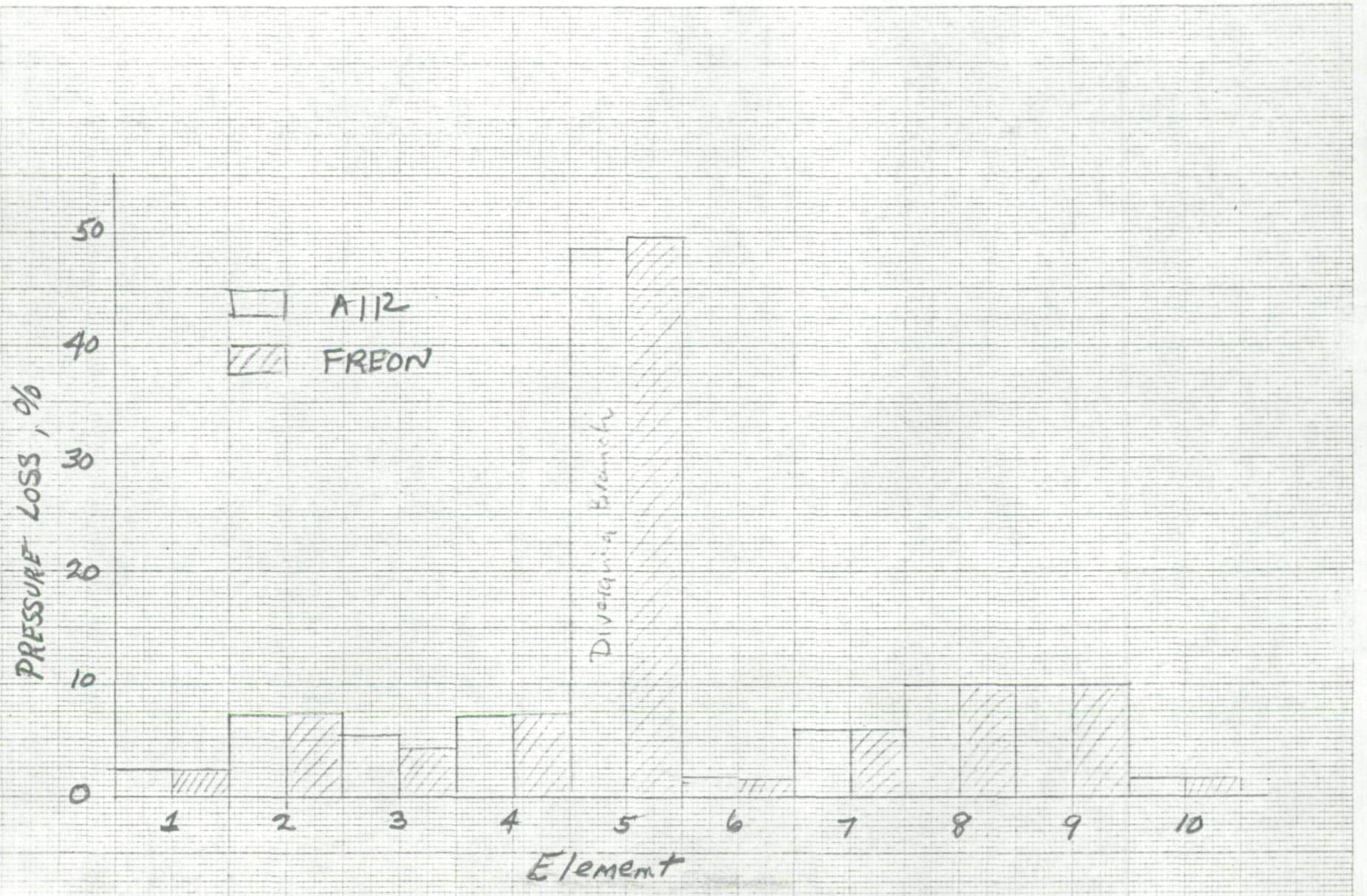

Fig. 4 Pressure Loss of various elements of the Auxiliary System Inlet Ducting, $M_{\infty} = 1.2$ and $W_A/W_T = 0.05$

5/30/73

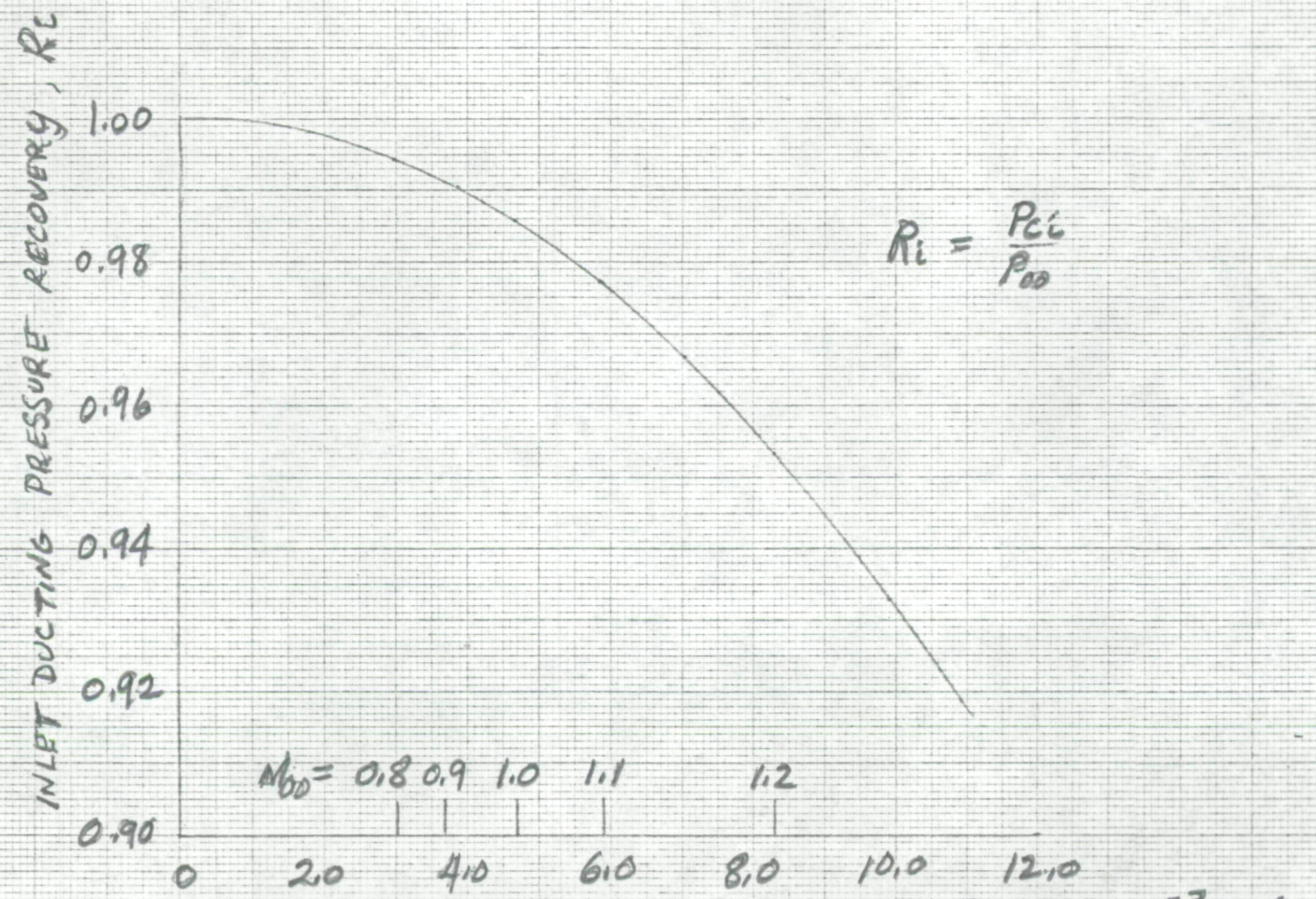

Fig 5 Pressure Recovery at the Auxiliary System Inlet Ducting with Freon as a test medium.

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5/30/73

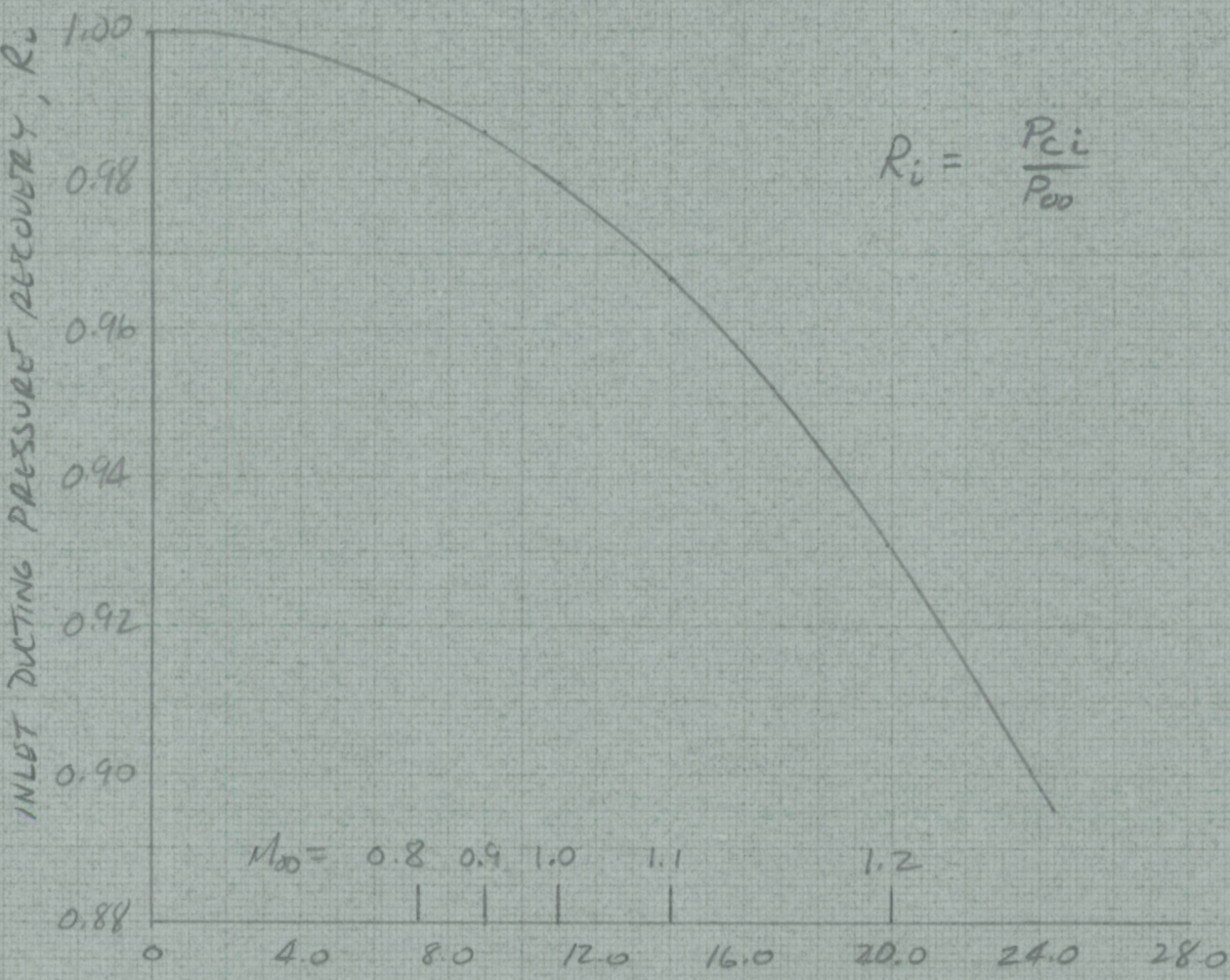

Fig. 6 Pressure Recovery of the Auxiliary System Inlet Ducting with AIR as a test Medium.

FMJ 5/30/73

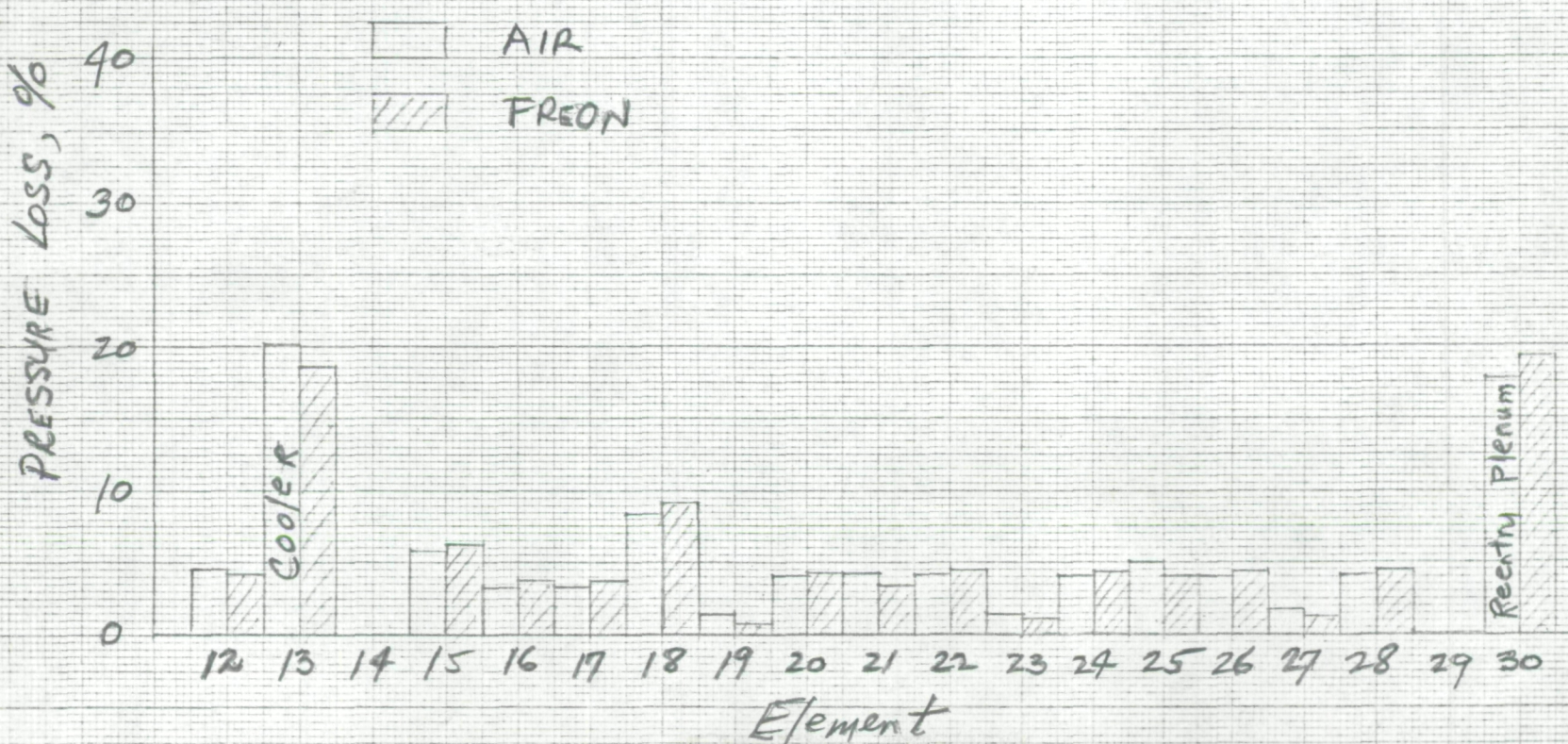

Fig 7. Pressure Loss of Various elements of the Auxiliary System Exit Ducting, $M_{\infty} = 1.2$, $W_A/W_T = 0.05$.

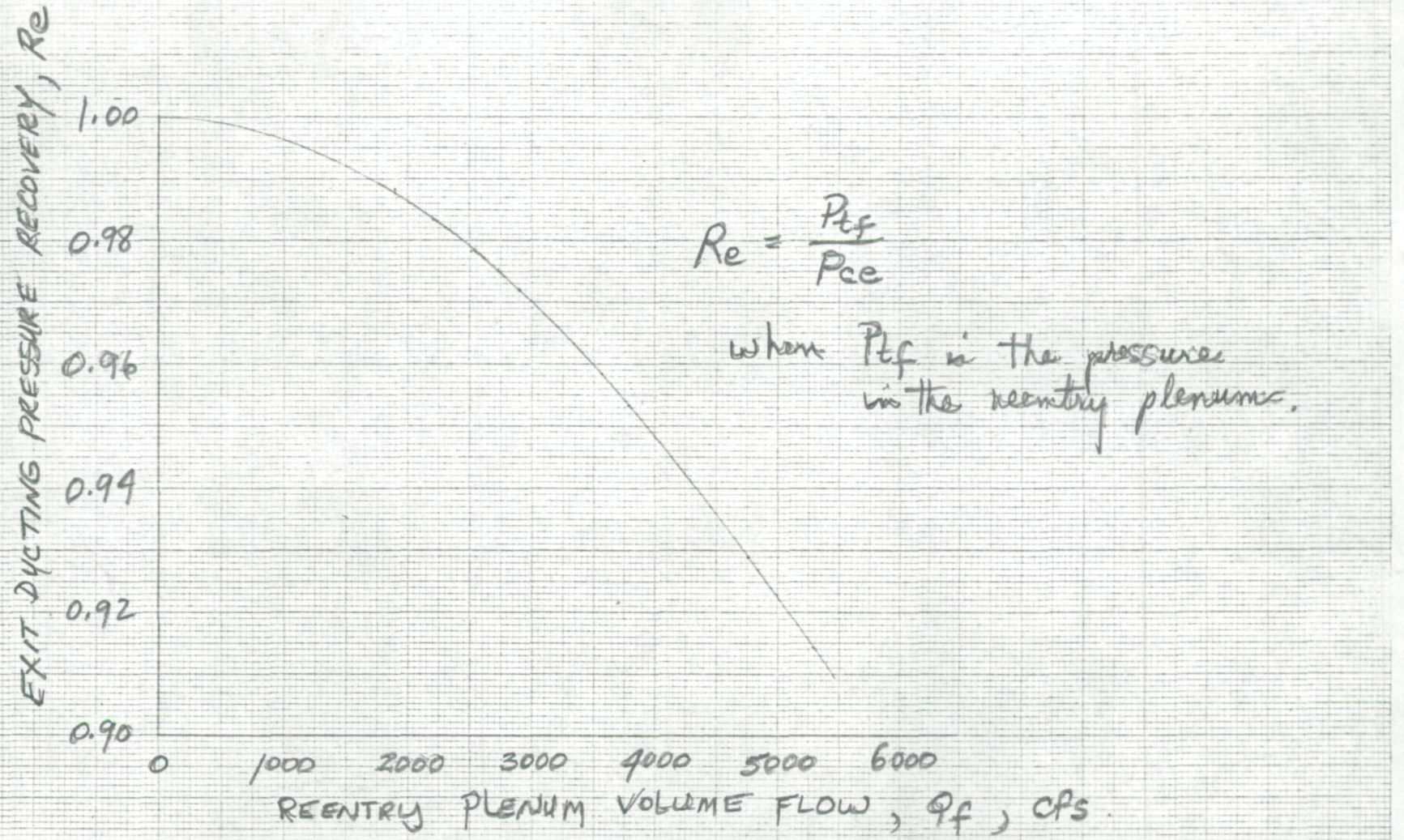

FIG 8 Pressure Recovery of the Auxiliary System Exit Ducting with Freon as a Test Medium

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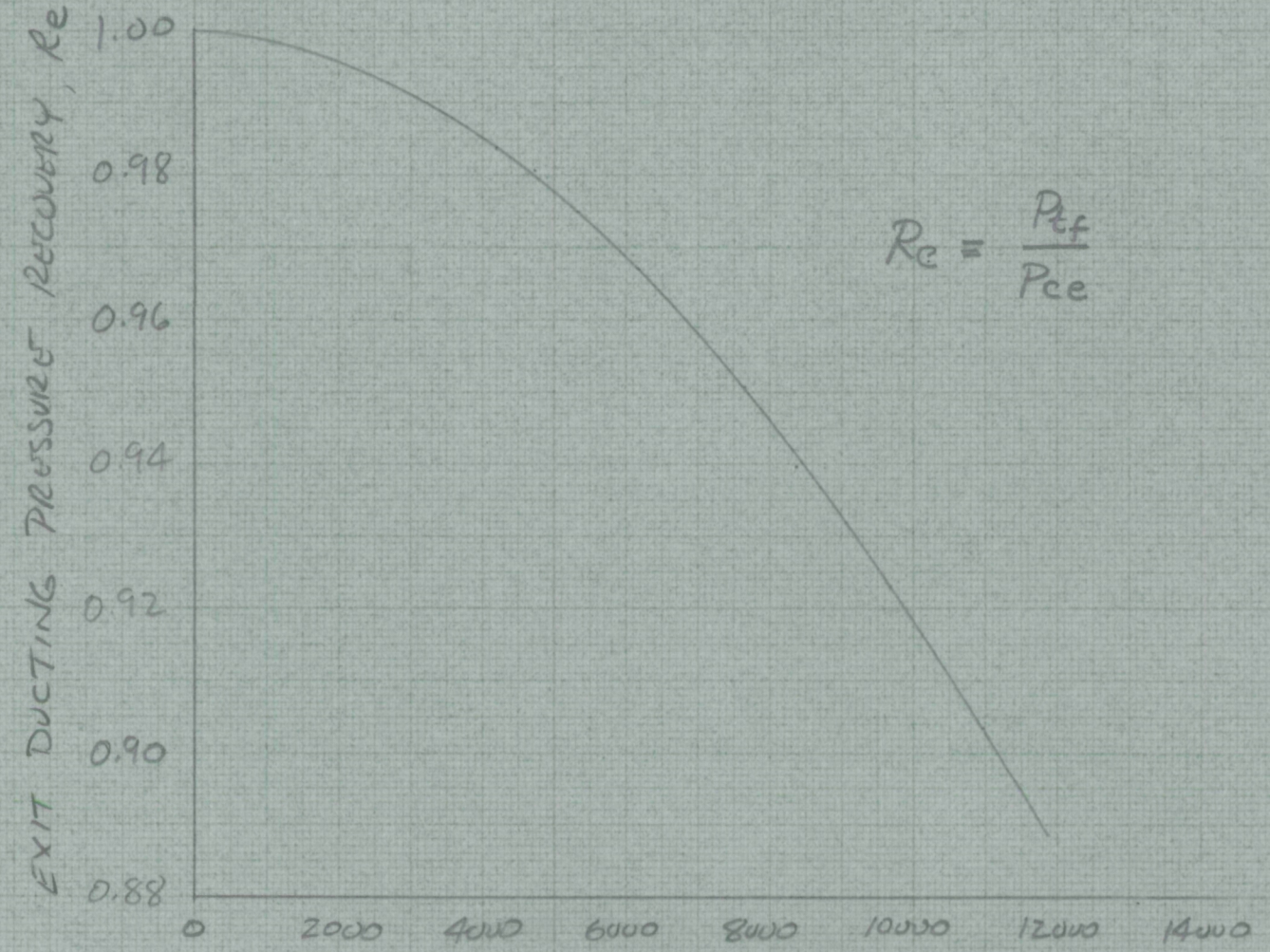

Fig 9 Pressure Recovery of the Auxiliary System Exit Ducting with Air as a Test Medium.

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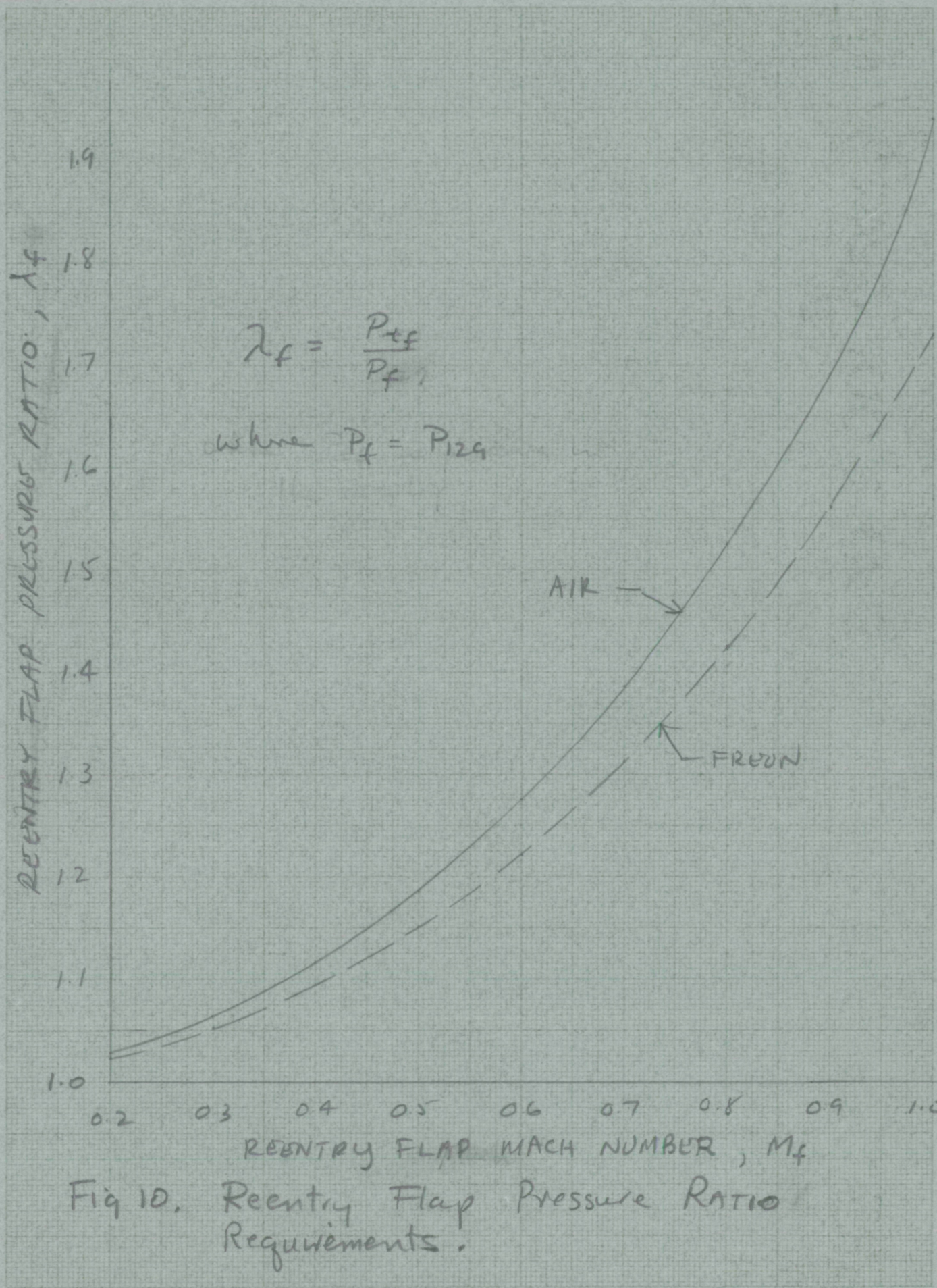

Fig 10. Reentry Flap Pressure Ratio Requirements.

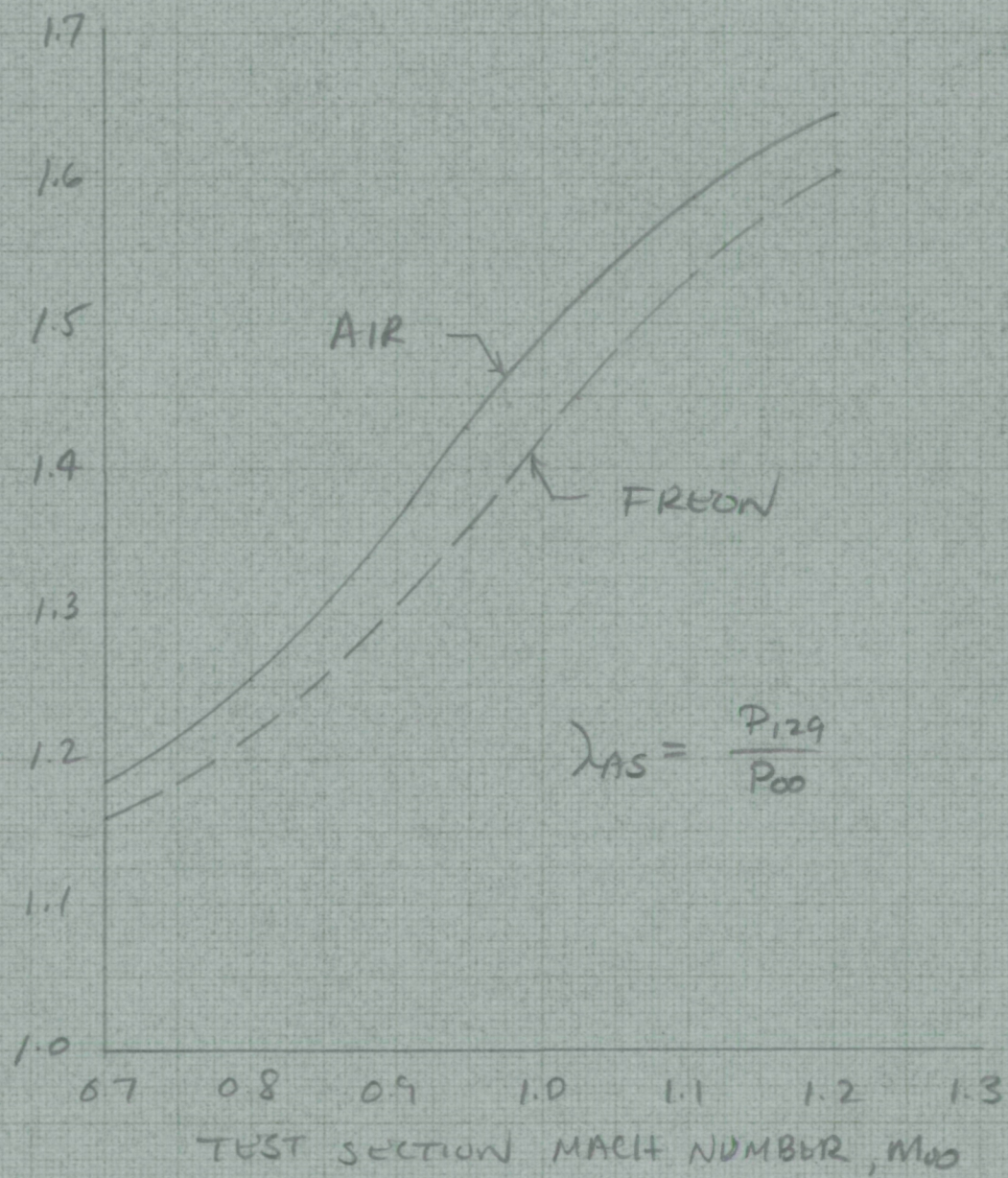

FIG 11. Auxiliary System Total Pressure Ratio Requirements.

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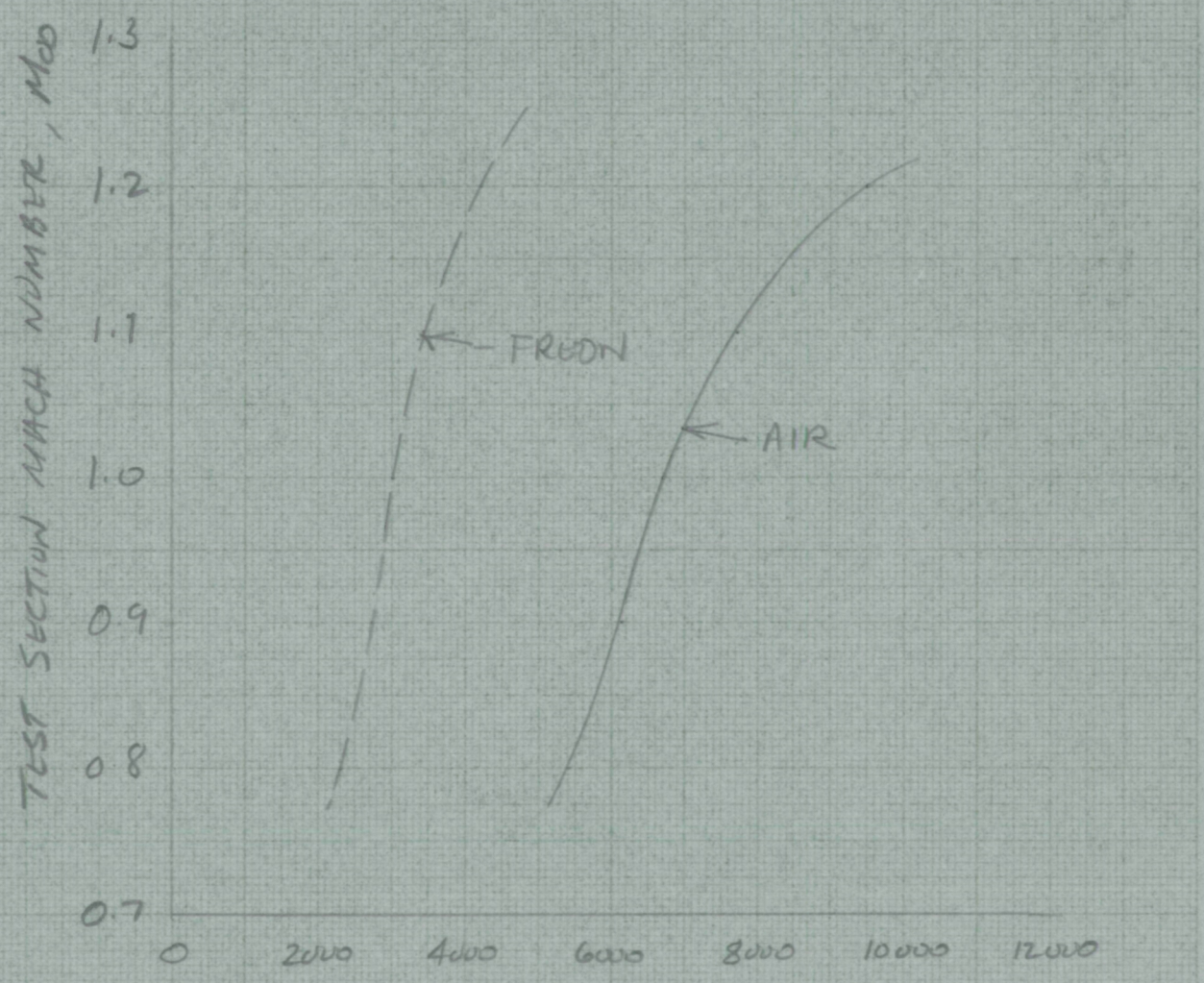

FIG 12 Reentry plenum Volume Flow Requirements for $A_f = 1.35\ ft^2$ and $T_t = 585°R$

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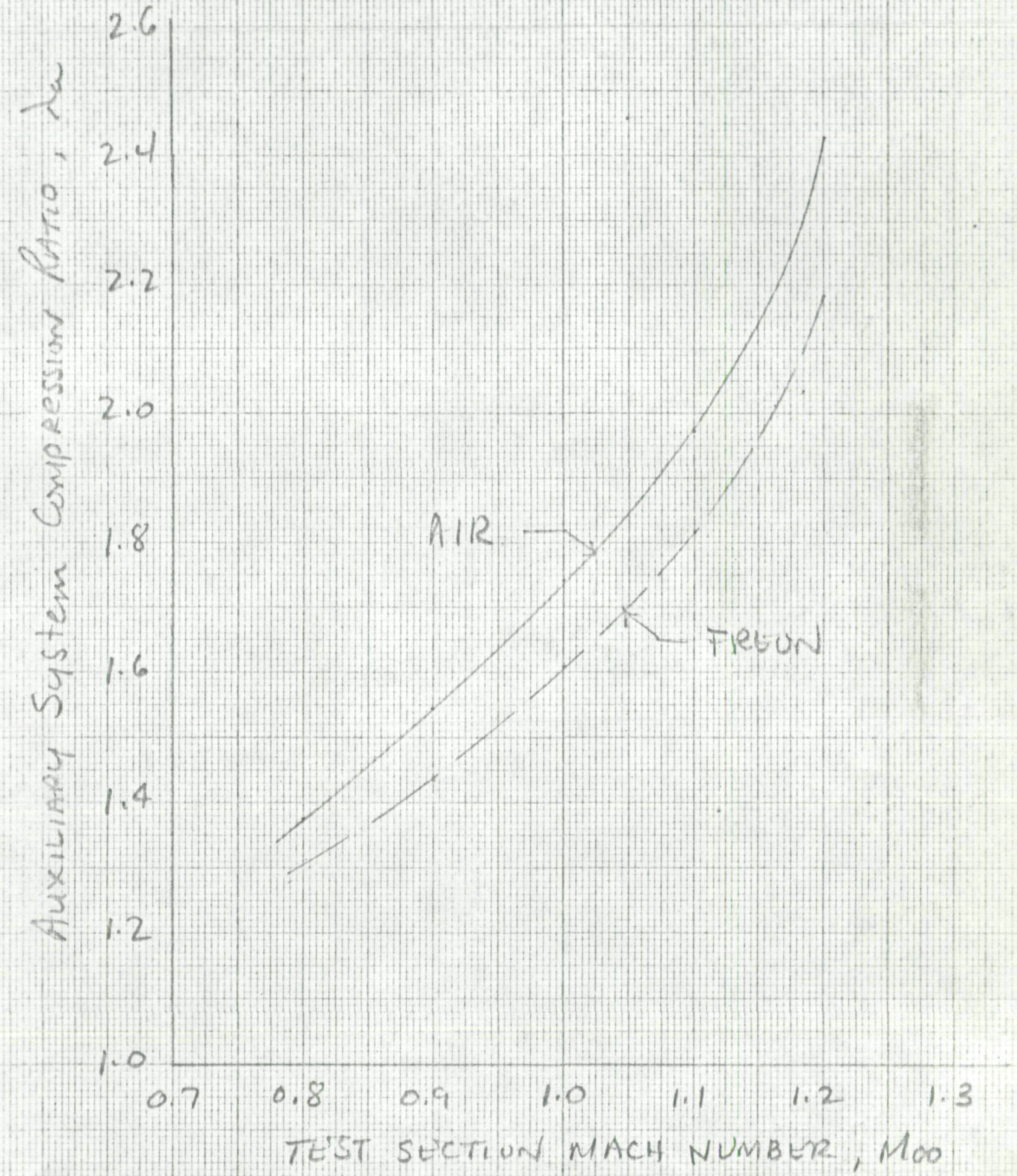

Fig 13. Auxiliary System Compressor Pressure Ratio Requirements.

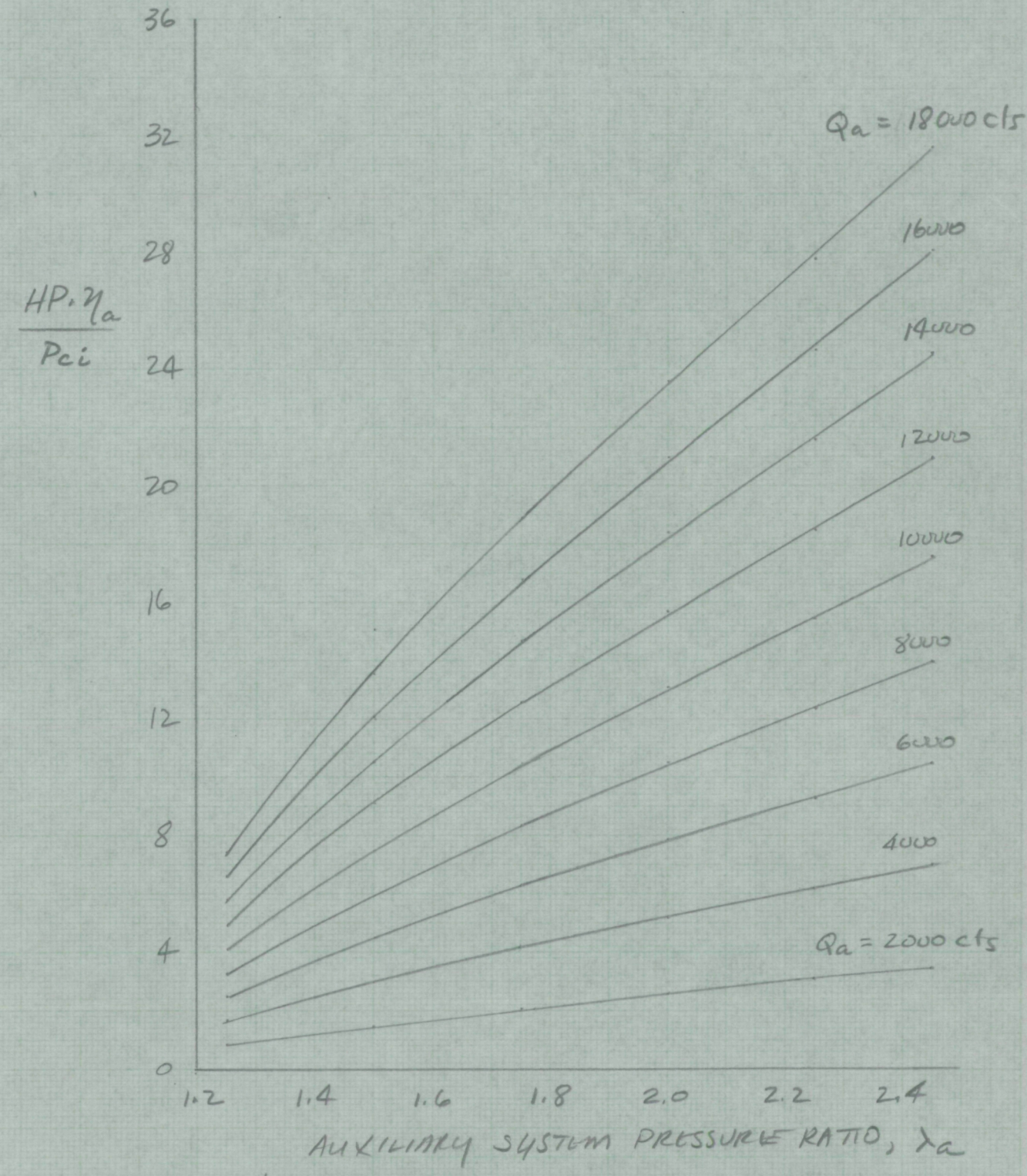

Fig 14. Horsepower Requirements for the Auxiliary System with Freon.

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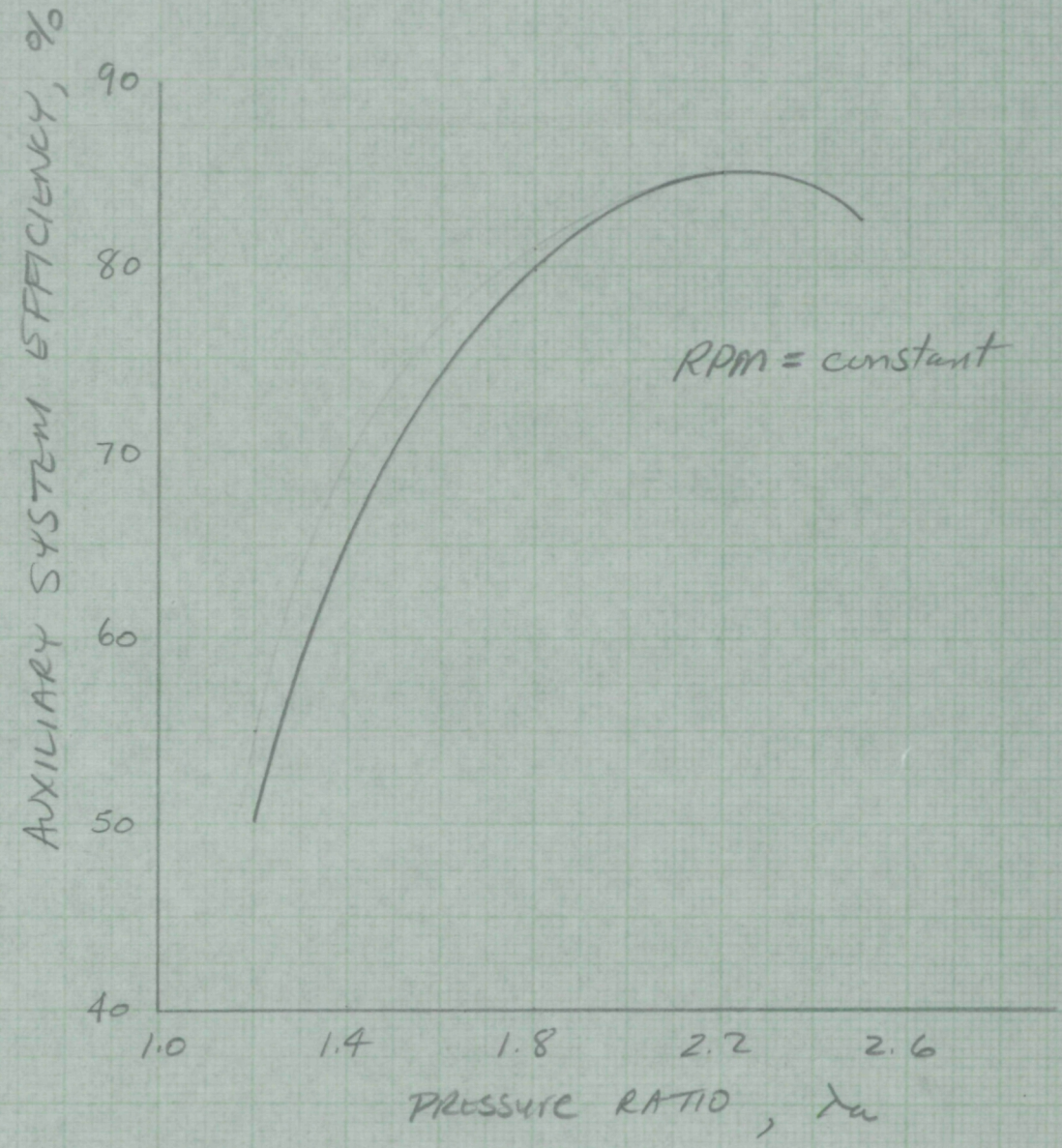

Fig 15. Assumed efficiency For the Aixiliary Compressor System with Freon as a Test Medium

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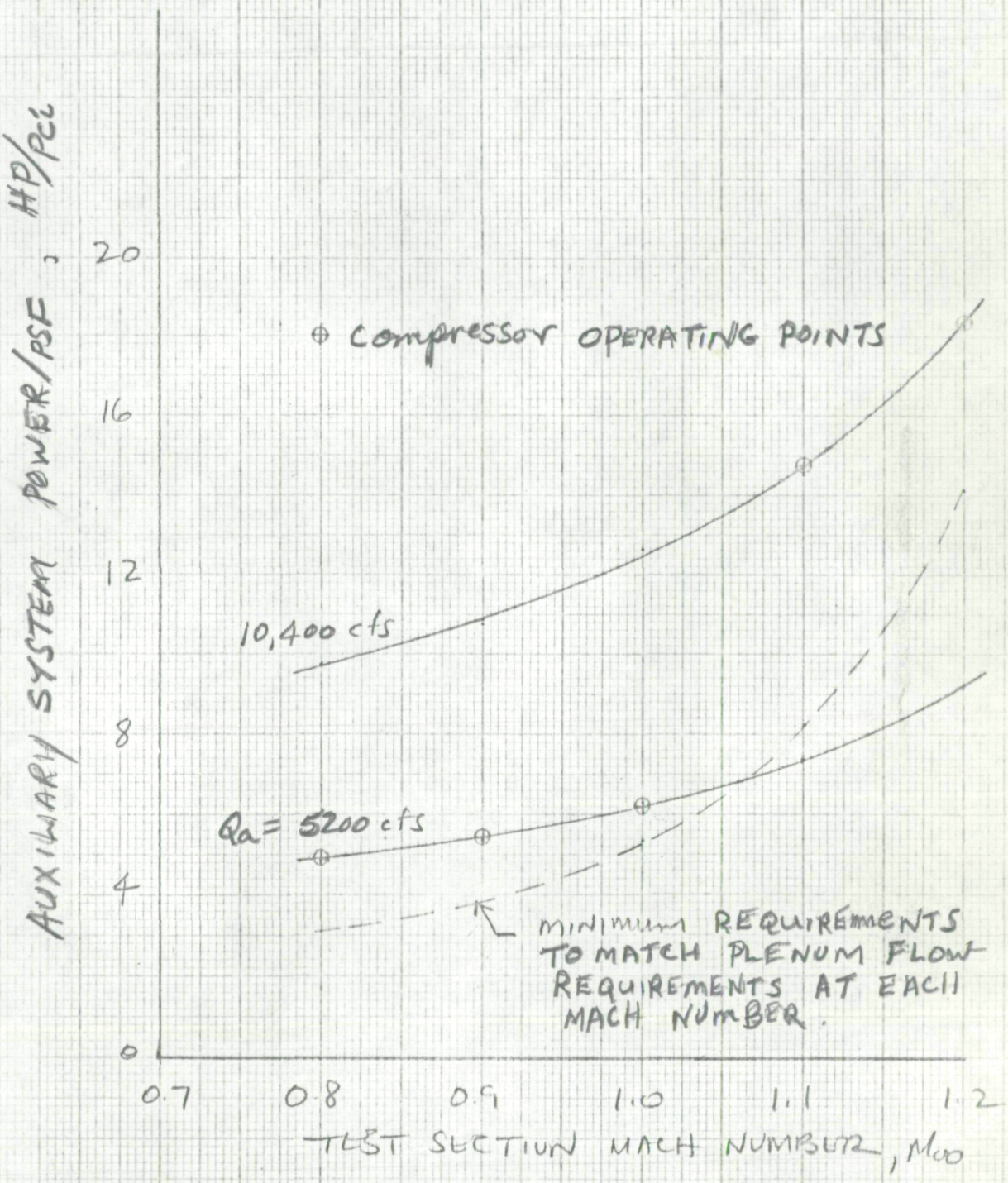

FIG. 16 Auxiliary System Power/PSF with Freon as a Test Medium.

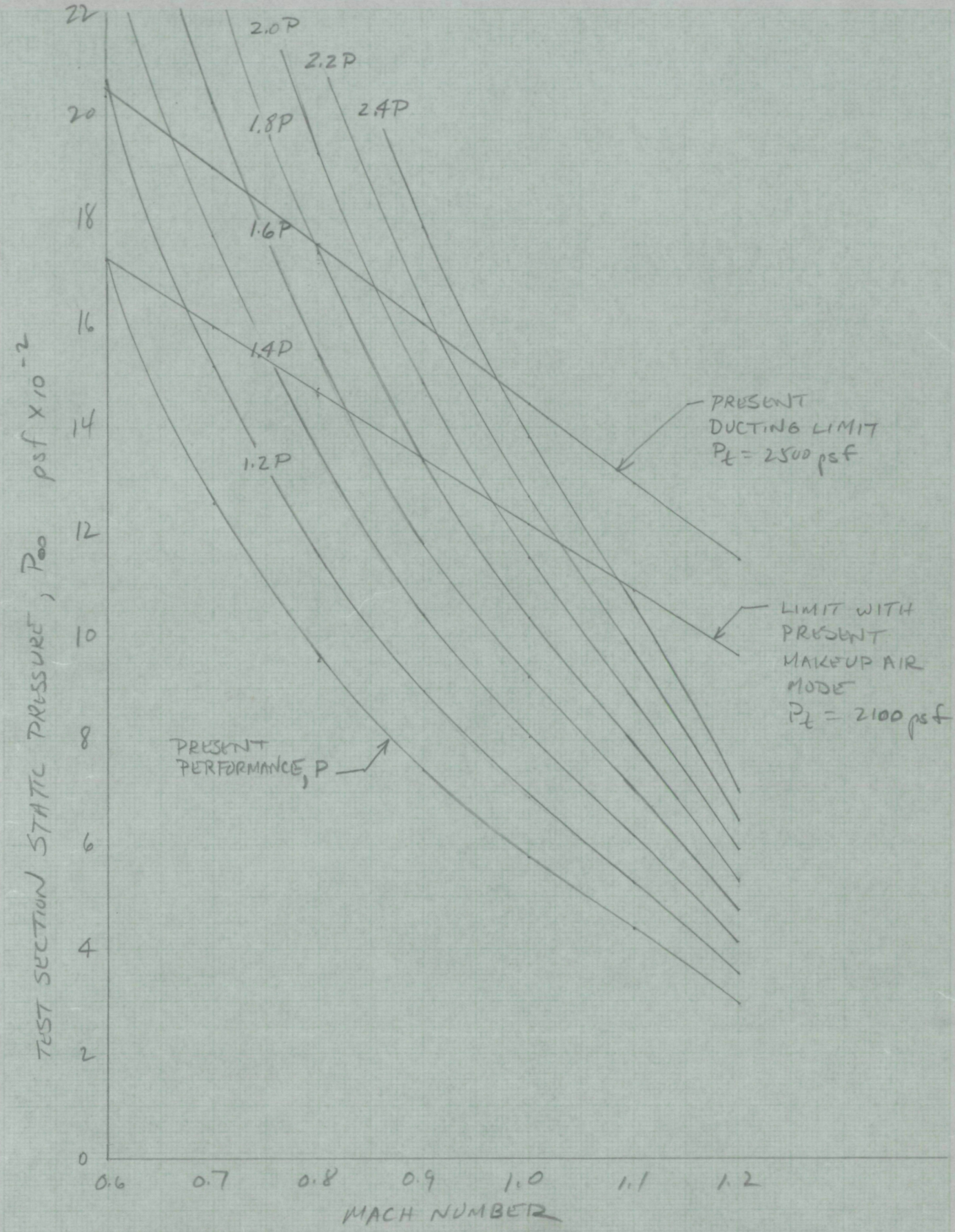

FIG 17. Variation of static pressure for Improved Performance with Freon.

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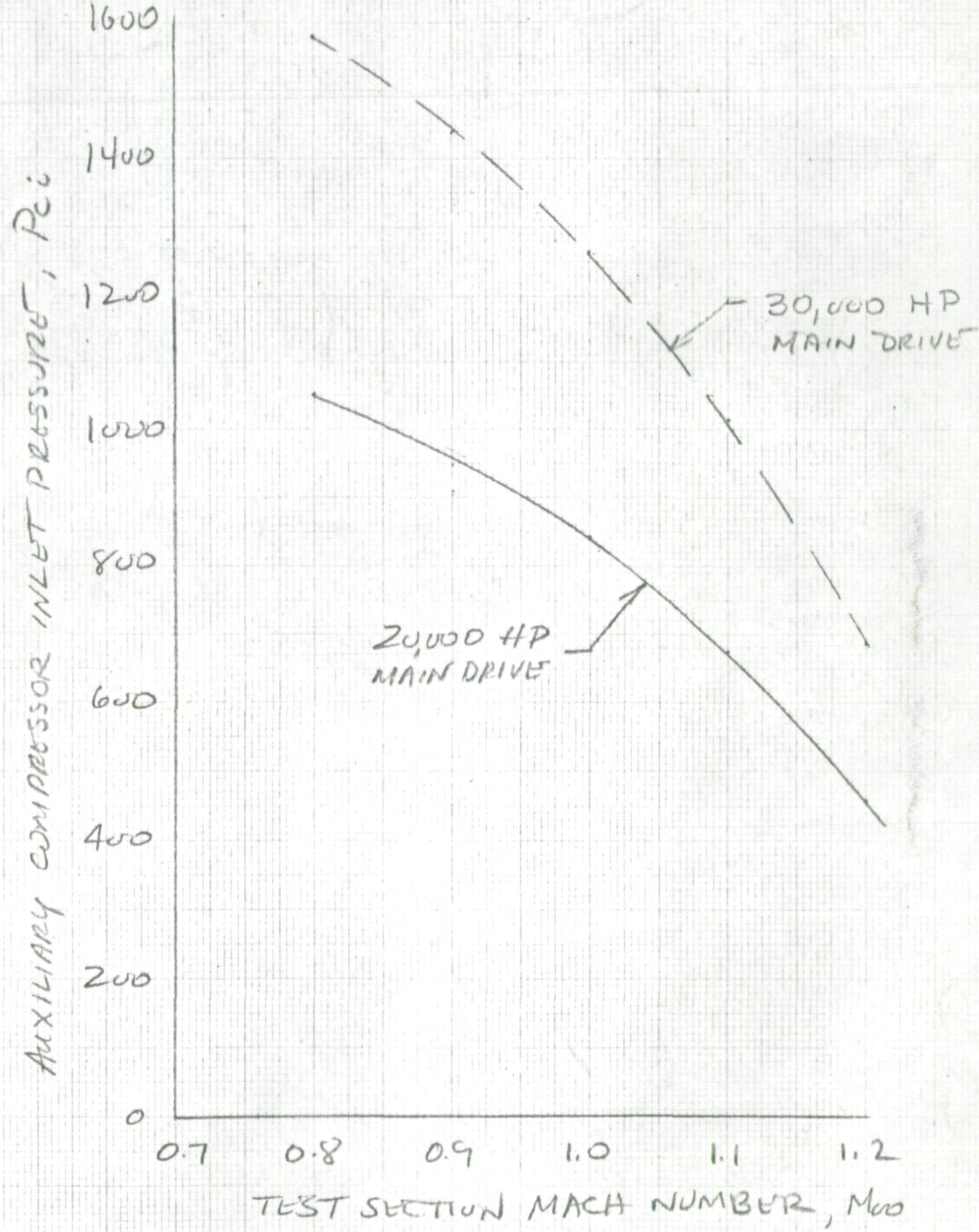

FIG 18 Auxiliary Systems Compressor Inlet pressure for a 20,000 and 30,000 HP MAIN DRIVE and WITH FREON as a test medium.

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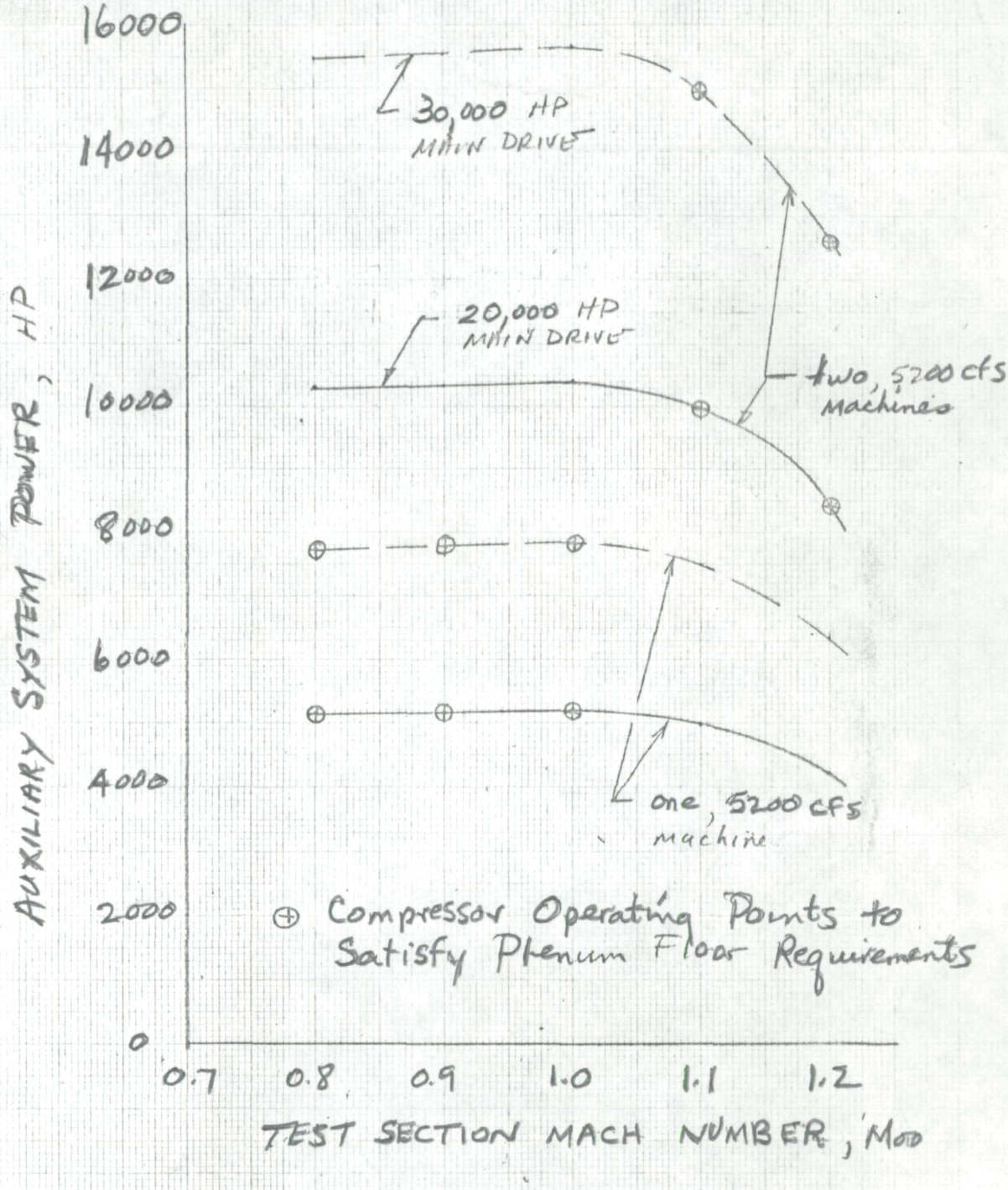

Fig 19. Auxiliary System Power Requirements for Freon with a 20,000 and 30,000 H.P. MAIN DRIVE.

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APPENDIX G

CIRCUIT PRESSURIZATION

STUDY OF STRUCTURAL CAPACITY OF
LANGLEY TRANSONIC DYNAMICS TUNNEL
(NASA)

1. One possible method of increasing the dynamic pressure, q, of this tunnel is to increase the total pressure of the test medium (either Freon-12 or air) above the present maximum operating pressure of 17.4 psia in the stagnation chamber immediately upstream of the nozzle inlet. Consideration is being given to increasing this pressure in increments up to a maximum as high as four times this value, or 69.6 psia. A general review of the effect of these incremental increases was made on various tunnel components to determine to what extent they would be affected structurally. The study and the conclusions are of a general nature because at this time none of the structural details of the tunnel are known.

The conclusions lead us to recommend limiting the proposed operating pressure increase to 125% of the Present Upper Operating Limit (PUOL) because the resulting increase in tunnel performance for an operating pressure increase to 200% of PUOL is below the range covered in the request for proposal for this study, and is not worth the added cost and increased hazards of operating at those higher pressures.

A proof pressure test of the tunnel is recommended before attempting to operate at higher pressures.

For this study, it was assumed that the future operating procedures will be similar to those currently being used. The tunnel circuit was considered to be divided into three zones with the static pressure within each zone remaining approximately the same. The zones are shown on Figure 1 and are as follows:

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COMPUTATIONS FOR TDT Study

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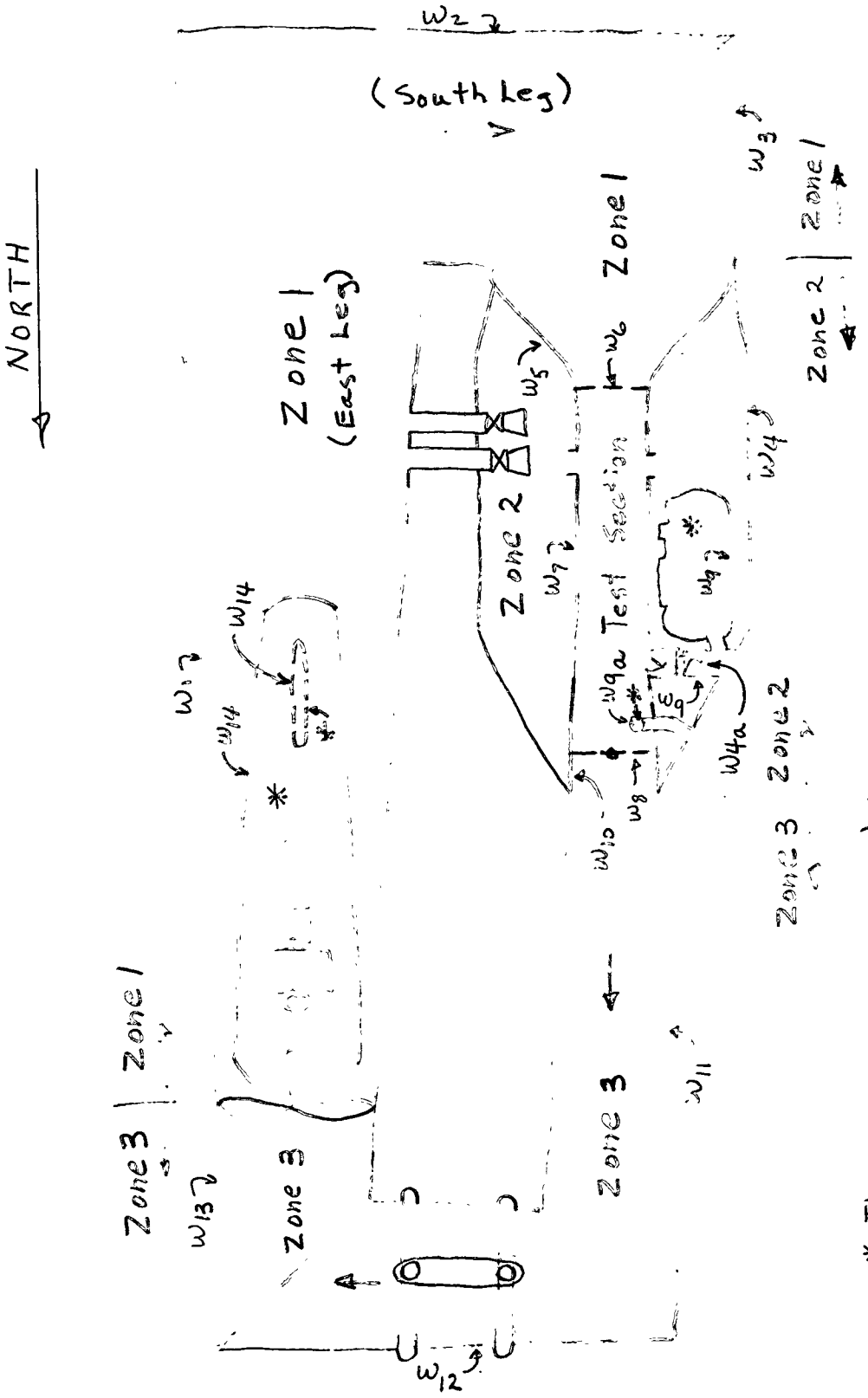

FIGURE 1

Zone 1 - from Fan to Test Section Inlet

Zone 2 - Test Section, including Plenum

Zone 3 - Downstream of Test Section to Fan

Approximate static pressures acting on the shell, the valves and other components were assumed for three tunnel operating conditions for each of a series of tunnel operating pressures. The three conditions are:

a. Tunnel circuit at operating pressure with fan running.

b. Full tunnel circuit, including test section, at operating pressure with fan off.

c. Test section at atmospheric pressure and isolated from remainder of tunnel circuit which is retained at operating pressure with fan off.

The assumed pressures are shown on Table 1.

2. Typical Present Tunnel Operation:

Tunnel shell is buttoned up, and pumped to operating pressure (either below or above atmospheric). The gas medium is usually Freon 12 which is heavier than air and is introduced into the bottom of the shell while the air is drawn off the top. At this point in time the entire shell feels the same pressure. Note that the central area of the Fan Drive Nacelle, the Personnel Access to the Nacelle, the Control Room, and the Observer's Dome and access Tube remain at atmospheric pressure at all times. Note also that the Test Section Plenum, the volume outside the Test Section and inside the 60 ft diam. duct, always feels the same pressure as inside the Test Section because it is vented to the test section.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

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TUNNEL SHELL STUDY RHW

TABLE I

	P_{Total} PSFA	FAN	VALVES Butterfly & Gate	Static Press. (psia) in Zone 1	2	3	Static Pressure on Wall - psig w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10}	w_{11}	w_{12}	w_{13}	w_{14}	Thrust on Rot. Joint Kips	Thrust on Control Room Kips	Thrust on Access Tube to Observation Port Kips	Proof Pressure Test psig
Present & Future Lower Operating Limit	29	ON	Open	0.2	0.1	0.2	-14.5	-14.5	-14.5	-14.6	+0.1	0	0	0	+14.6	+0.1	-14.5	-14.5	-14.5	+14.5	-2,009	+59.4	+14.9	Not Applicable
	—	OFF	Open	0.2	0.2	0.2	-14.5	-14.5	-14.5	-14.5	0	0	0	0	+14.5	0	-14.5	-14.5	-14.5	+14.5	"	+59.0	+14.8	
	—	OFF	Closed	0.2	14.7	0.2	-14.5	-14.5	-14.5	0	-14.5	14.5 →	0	← 14.5	0	-14.5	-14.5	-14.5	-14.5	+14.5	"	0	0	
Present Upper Operating Limit	2500	ON	Open	17.4	8.7	14.5	+2.7	+2.7	+2.7	-6.0	-5.7	0	0	0	+6.0	+5.8	-0.2	-0.2	-0.2	-2.7	-28	+24.4	+6.1	Not Applicable
	—	OFF	Open	14.5	14.5	14.5	-0.2	-0.2	-0.2	-0.2	0	0	0	0	+0.2	0	-0.2	-0.2	-0.2	+0.2	"	+0.8	+0.2	
	—	OFF	Closed	14.5	14.7	14.5	-0.2	-0.2	-0.2	0	-0.2	0.2 →	0	← 0.2	0	-0.2	-0.2	-0.2	-0.2	+0.2	"	0	0	
150% of POOL	3750	ON	Open	26.0	13.0	21.6	+11.3	+11.3	+11.3	-1.7	+13.0	0	0	0	+1.7	+8.6	+6.9	+6.9	+6.9	-11.3	+956	+6.9	+1.7	—
	—	OFF	Open	21.6	21.6	21.6	+6.9	+6.9	+6.9	+6.9	0	0	0	0	-6.9	0	+6.9	+6.9	+6.9	-6.9	"	-28.1	-7.0	-14.5 +17.0
	—	OFF	Closed	21.6	14.7	21.6	+6.9	+6.9	+6.9	0	+6.9	6.9 →	0	← 6.9	0	+6.9	+6.9	+6.9	+6.9	-6.9	"	0	0	-14.5 +10.4
200% of POOL	5,000	ON	Open	34.8	17.4	29.8	+20.1	+20.1	+20.1	+2.7	+17.4	0	0	0	-2.7	+12.4	+15.1	+15.1	+15.1	-20.1	+2,092	-11.0	-2.7	—
	—	OFF	Open	29.8	29.8	29.8	+15.1	+15.1	+15.1	+15.1	0	0	0	0	-15.1	0	+15.1	+15.1	+15.1	-15.1	"	-61.4	-15.4	-14.5 +30.2
	—	OFF	Closed	29.8	14.7	29.8	+15.1	+15.1	+15.1	0	+15.1	15.1 →	0	← 15.1	0	+15.1	+15.1	+15.1	+15.1	-15.1	"	0	0	-14.7 +22.7
300% of POOL	7,500	ON	Open	52.2	26.1	43.5	+37.5	+37.5	+37.5	+11.4	+26.1	0	0	0	-11.4	+17.4	+28.8	+28.8	+28.8	-37.5	+3,990	-46.4	-11.6	—
	—	OFF	Open	43.5	43.5	43.5	+28.8	+28.8	+28.8	+28.8	0	0	0	0	-28.8	0	+28.8	+28.8	+28.8	-28.8	"	-117.2	-29.3	-14.5 +56.3
	—	OFF	Closed	43.5	14.7	43.5	+28.8	+28.8	+28.8	0	+28.8	28.8 →	0	← 28.8	0	+28.8	+28.8	+28.8	+28.8	-28.8	"	0	0	-14.5 +43.2
400% of POOL	10,000	ON	Open	69.6	34.8	58.0	+54.9	+54.9	+54.9	+20.1	+34.8	0	0	0	-20.1	+23.2	+43.3	+43.3	+43.3	-54.9	+5,999	-81.8	-20.5	—
	—	OFF	Open	58.0	58.0	58.0	+43.3	+43.3	+43.3	+43.3	0	0	0	0	-43.3	0	+43.3	+43.3	+43.3	-43.3	"	-176.1	-44.1	-14.5 +82.4
	—	OFF	Closed	58.0	14.7	58.0	+43.3	+43.3	+43.3	0	+43.3	43.3 →	0	← 43.3	0	+43.3	+43.3	+43.3	+43.3	-43.3	"	0	0	-14.5 +65.0
125% of POOL	3125	ON	Open	21.8	10.9	18.2	+7.1	+7.1	+7.1	-3.8	+10.9	0	0	0	+3.8	+7.3	+3.5	+3.5	+3.5	-7.1	+485	+15.5	+3.9	—
	—	OFF	Open	18.2	18.2	18.2	+3.5	+3.5	+3.5	+3.5	0	0	0	0	-3.5	0	+3.5	+3.5	+3.5	-3.5	"	-14.2	-3.6	-14.5 +10.7
	—	OFF	Closed	18.2	14.7	18.2	+3.5	+3.5	+3.5	0	+3.5	3.5 →	0	← 3.5	0	+3.5	+3.5	+3.5	+3.5	-3.5	"	0	0	-14.5 +5.3

The fan is then started, which results in a pressure differential throughout the tunnel circuit. A series of static pressure profiles should be made up for all proposed operating conditions. (The static pressure is the pressure that the walls feel, and that is needed to determine the tunnel structural limits).

During a test run it is often necessary to enter the test section to make some adjustment on the model. At such a time the fan is stopped and the gas pressure inside the tunnel quickly stabilizes throughout the system. The Butterfly Valve and the Gate Valve are both closed then, the Freon-12 is pumped out, and air is introduced into the Test Section and Test Section Plenum bringing this chamber to atmospheric pressure. This results in either a positive or negative pressure on the Butterfly Valve, the Gate Valve, the Nozzle Inlet fairing upstream of the Gate Valve, and the Diffuser Inlet immediately downstream of the Butterfly Valve, depending on the stabilized gas pressure inside the remainder of the Tunnel Circuit. After the adjustment on the Model has been made, the tunnel is readied for additional testing by reversing the procedures described in this paragraph.

It is assumed that there would never be a time when the Butterfly and Gate valves would be closed and Freon would be retained in the Test Section and Test Section Plenum while Freon would be removed and air added to the rest of the circuit.

3. Effect of Increased Pressure on Specific Components of Pressure Shell

a. Zone 1, from approximately 50 feet downstream of Fan to Test Section Inlet. This portion of the tunnel shell is part of

the original tunnel shell that was designed for a pressure of $2\frac{1}{2}$ atmospheres absolute or +22.0 psig internal pressure. When the TDT was rebuilt in the late 1950's to operate as a vacuum tunnel down to a pressure of 0.2 psia or -14.5 psig external pressure, additional ribs were added between the existing ribs on the shell, a new elliptical girder with turning vanes and a two-row vertical cooler were provided at the southeast corner, and the elliptical girder at the southwest corner was reinforced and had a vertical air-foil-shaped strut added to the inside corner. The reason for adding this strut is not readily apparent.

(1) Pressure Shell and Southwest Corner Girder, W_2, W_3, and part of W_1:

The shell in this zone and the elliptical girder in the southwest corner are almost certainly suitable for 150% PUOL without additional reinforcement being added, and are probably suitable for 200% of PUOL. However, suitability of these elements in each of these cases is dependent on the details of the stiffening ribs or tees that were added to the shell, and the reinforcement that was added to the elliptical girder. It is possible, though unlikely, that these details would make the tunnel in this zone less suitable than for the original +22.0 psig design pressure, and these details would have to be reviewed during final design. Consideration would also have to be given to the stress reversals that would occur under some test conditions with these higher operating pressures. These elements are unlikely to be found suitable for pressures of 300% or more of PUOL without some additional strengthening which would be impractical, if not impossible.

(2) Southeast Corner Girder: Since a new elliptical girder was provided in the southeast corner when the tunnel was modified, it is safe to assume that this girder has never been subjected to internal operating pressures much above 3.0 psig, although it is known to have been frequently subjected to external pressures of -14.5 psig. Its ability to withstand 150% or 200% of PUOL is dependent on its details. The design and details of this girder will have to be carefully scrutinized during final design to determine what kind of reinforcement, if any, would be required to make it suitable for these greater internal pressures. It may even be necessary to replace this girder to attain 150% or 200% of PUOL although this is unlikely. At any rate, it is unlikely that this girder will be found to be suitable for pressures of 300% or more of PUOL without some additional strengthening which would be impractical if not impossible.

b. Zone 2, Test Section including Plenum

This portion of the tunnel outer pressure shell is part of the original tunnel shell that was designed for an operating pressure in the stagnation chamber upstream of the nozzle entrance of +22.0 psig. Presumably the test section plenum held pressures of about +22.0 psig when the original tunnel was buttoned up and pressurized with the test section isolation valves open and the fan off. And, presumably it was subjected to the same test pressure as the ducting upstream of the test section before the tunnel was placed

in operation. When the TDT was modified to operate as a vacuum tunnel, the four stiffening girders were reinforced and additional ribs were added between the existing ribs on the shell. At that time the air stream shell (consisting of the nozzle, the test section, and the diffuser inlet), the control room, the personnel access to the test section, and the observation dome and its access tube were added, and the personnel and the model access openings may have been modified.

(1) External Pressure Shell, W4: The external shell in this zone is almost certainly suitable for 150% of PUOL without any additional reinforcement being added, and is probably suitable for 200% of PUOL without additional reinforcement, since the design pressure for 200% of PUOL is about equal to the original design pressure (which has been assumed without the benefit of the original design criteria). However, suitability of this pressure shell is dependent on the details of the stiffening ribs or tees that were added to the shell and the reinforcement that was added to the four main stiffening girders. It is possible, though unlikely, that these details would make this shell less suitable than for the original design pressure, and these details would have to be reviewed during final design. Consideration has to be given also to the stress reversals that will result from the increased operating pressures. This shell is unlikely to be found suitable for pressures of 300% or more of PUOL without some additional strengthening which would

be impractical if not impossible. This is especially true of the reinforcement details for the personnel and model access openings. The details of these doors, and the reinforcement of the openings in the shell will require close scrutiny to satisfy oneself that they are suitable even for 150% or 200% of PUOL.

(2) Nozzle Inlet Fairing, W_5: Under present operating proceedures, this fairing is subjected at times to an external pressure of -14.5 psig and at other times to an internal pressure of approximately +8.7 psig. This fairing is probably suitable for 150% of PUOL without any additional reinforcement. It may be suitable for 200% of PUOL without any additional reinforcement, although under these pressures the stress reversals would be 100% and could occur several times for some test runs under normal operating procedures. The details of this fairing would have to be carefully reviewed during final design to determine if it is indeed suitable for either 150% or 200% of PUOL. At 200% or more of PUOL, the design consideration for the internal pressure on this fairing would be the pneumatic pressure proof test that would be required. It is very unlikely that this fairing will be found to be suitable for 300% or more of PUOL without additional strengthening that would be impractical if not impossible.

(3) Test Section Airstream Shell between Test Section Isolation Valves, W_7: This fairing, being vented to the test section plenum, senses very little pressure differential under the present operating conditions, and this would

be true under anticipated future operating conditions. This fairing is suitable, without additional strengthening, for pressures up to 400% of PUOL.

(4) Gate Valve (Test Section Isolation Valve), W_6: This valve was added when the tunnel was rebuilt. Under present operating conditions it is subjected to pressure differentials, when closed, that vary from about 0 to 14.5 psig with the pressure always acting in a southward direction. This valve may be suitable for 150% of PUOL, although for this condition the direction of pressure would be reversed and the differential would be about 6.9 psig. This valve may even be suitable for 200% of PUOL, although for this condition the direction of pressure would also be reversed and the differential would be increased to about 15.1 psig. Whether or not it would be suitable for either 150% or 200% of PUOL depends on the details of the valve itself, including its seat and its mounting details, all of which would have to be carefully reviewed during final design. Also, consideration would have to be given to the resulting stress reversals. It is almost certain that this valve would not be suitable for 300% or more of PUOL and a new valve would be required for this condition.

(5) Butterfly valve (Test Section Isolation Valve), W8: This valve was added when the tunnel was rebuilt. Underpresent operating conditions it is subjected to pressure differentials, when closed, that vary from about 0 to 14.5 psig with the pressure always acting in a northward direction. This valve is almost certain to be suitable

for 150% of PUOL, although for this condition the direction of pressure would be reversed and the differential would be about 6.9 psig. This valve is probably suitable for 200% of PUOL, although for this condition the direction of pressure would also be reversed and the differential would be increased to about 15.1 psig. Whether or not it would be suitable for either 150% or 200% of PUOL depends on the details of the valve itself and its mounting details, all of which would have to be carefully reviewed during final design along with the resulting stress reversals. It is almost certain that this valve would not be suitable for 300% or more of PUOL and a new valve would be required for this condition.

(6) Diffuser Inlet between Butterfly Valve and Downstream end of Test Section Plenum, W_{10}: This part of the shell is new ducting that was added when the TDT was rebuilt. Under present operating conditions, the pressure on this shell varies from 14.5 psig external pressure to approximately 5.8 psig internal pressure. Without additional reinforcement, this shell will almost certainly be suitable for 150% of PUOL and will probably be suitable for 200% of PUOL at which condition the internal pressure on this shell would increase to about 15.1 psig. Its suitability will depend on the welding details that were used on this shell. If full penetration butt welds were used in the longitudinal seams, and preferably in the circumferential seams also, it will be suitable for 200% of PUOL. At 150% or more of PUOL, the design consideration for the internal pressure on this ducting will be the pneumatic pressure

proof test that would be required. These welding details will have to be reviewed during final design, along with the stress reversals. This shell may even be suitable for the 300% and 400% of PUOL condition, although it is unlikely that it will be suitable for these pressures.

(7) Observation Dome and Access Tube, W_{9a}: These are new items that were added when the TDT was rebuilt. Under present operating conditions, this dome and access tube are subjected to an internal pressure varying from about 0.2 to 14.6 psig.

At 150% of PUOL they would be subjected to an external pressure of about 6.9 psig and at 200% of PUOL an external pressure of about 15.1 psig. It is possible that either or both the steel shell and the glass window may not be suitable for these new pressures. In that case it would be preferable to remove the observation dome and the access tube rather than to attempt to reinforce these items. Since this dome is practically never used, it would be preferable to remove it even if it did not require strengthening because its removal would contribute an improvement to the stream flow. This is another detail that would have to be reviewed during final design. At 150% or more of PUOL, the design consideration for the external pressure on this dome and tube will be the pneumatic pressure proof test that would be required. It is unlikely that these items will be satisfactory for 300% or more of PUOL.

(8) Control Room, W_9: Under present operating conditions this chamber is subjected to an internal pressure varying from about 0.2 to 14.6 psig. At 150% of PUOL it would be subjected to an external pressure of about 6.9 psig, and at 200% of PUOL an external pressure of about 15.1 psig.

(a) Pressure Shell of Control Room: At 150% of PUOL, the shell may not require additional stiffening, although it is very probable that it will require the addition of external ribs, and it will be subjected to several stress reversals on some test runs. At 200% of PUOL the shell will almost certainly require the addition of external ribs and it will be subjected to several stress reversals of about 100% on some test runs. At 150% or more of PUOL the design consideration on the Control Room will be the pneumatic pressure proof test that would be required. For 300% or more of PUOL it will probably not be practical to strengthen this chamber and a new chamber may be required. A careful review of the details of the Control Room will have to be made during final design. To cancel the need for strengthening this pressure shell as well as some of the other components discussed in paragraphs (b), (c), (d), (e), and (f) below, consideration could be given to pressurizing the Control Room. This would be an undesirable solution as far as operating personnel are concerned and would place undesirable operating constraints on the tunnel.

(b) Observation Windows: The window details may require modification to be suitable for either 150% or 200% of PUOL. They will require a careful review during final design. At 150% or more of PUOL the proof test may control the design of these details. New details will almost certainly be required for 300%or more of PUOL. There will be stress reversals in the glass of about 50% for the 150% of PUOL and of 100% for the 200% of PUOL conditions.

(c) Personnel Access to Control Room: At 150% of PUOL the reinforcement of the Control Room shell for the Personnel access opening will probably not require strengthening although it will be subjected to several partial stress reversals on some test runs. At 200% of PUOL it may not require strengthening although it will be subjected to several stress reversals of about 100% on some test runs. Again, the effect of the proof test will have to be considered. For 300% or more of PUOL it will probably not be practical to strengthen this opening in the Control Room shell. This will have to be reviewed in detail during final design.

(d) Net Thrust on Control Room: Under present operating conditions the net thrust acting on the Control Room is a force that varies from 0 to about 60 kips and tends to separate the control room from the Test Section Plenum Shell. At 150% of PUOL the net thrust will be reversed and will be reduced to about 28 kips

which will in no way harm the joint and will probably not have an adverse effect on the access tunnel that it connects to. At 200% of PUOL the net thrust will be reversed from its present direction and will be equal to about 61K which will in no way harm the joint but may have an adverse effect on the access tunnel. This problem will have to be studied during final design and the effect of the proof test will have to be considered. At 300% or more of PUOL, the thrust will increase considerably and probably will have an adverse effect on the access tunnel requiring some strengthening of the access tunnel.

(e) Personnel Access Door to Test Section: This door is currently subjected to external pressures tending to close it varying from about 0.2 to 14.5 psig. For 150% of PUOL it would be subjected to internal or opening pressures of about 6.9 psig and for 200% of PUOL to internal pressures of about 15.1 psig. These pressures will cause stress reversals up to 100% under some operating conditions. For each of these conditions, the door itself may be suitable, but the door attachments will have to be reviewed and will probably have to be revised. At 150% or more of PUOL the design consideration for the opening pressure on this door will be the pneumatic pressure proof test. A new door would probably be required for 300% or more of PUOL.

(f) Access Tunnel to Test Section through Test Section Plenum: That part of the Access Tunnel between the airstream surface and the pressure-tight door is not subjected to

any appreciable pressure differential and would be suitable for any tunnel operating pressure increase up to 400% of PUOL. That part of the Access Tunnel between the pressure-tight door and the test section plenum shell is currently subjected to an internal pressure of about 14.6 psig. For 150% of PUOL, it would be subjected to an external pressure of about 6.9 psig and would probably not require strengthening although it will be subjected to several partial stress reversals on some test runs. At 200% of PUOL it may not require strengthening, although it probably will, since it would be subjected to several stress reversals of about 100% on some test runs. At 150% or more of PUOL one design consideration for the external pressure on this access Tunnel will be the pneumatic pressure proof test. It is unlikely that this access tunnel will be suitable for 300% or more of PUOL.

c. Zone 3, from Test Section Exit to Upstream End of Northwest Corner Girder, W_{11}.

This portion of the tunnel is part of the original tunnel shell that was designed for an internal operating pressure in the stagnation chamber upstream of the nozzle entrance of +22.0 psig. Presumably this part of the ducting was subjected to pressures of about 22.0 psig when the original tunnel was buttoned up and pressurized with the test section isolation valves open and the fan off. When the TDT was modified to operated as a vacuum tunnel, additional ribs were added between the existing ribs on the shell.

This ducting is almost certainly suitable for 150% of PUOL without any additional reinforcement being added, and is probably suitable for 200% of PUOL without any additional reinforcement, since the design pressure for 200% of PUOL is about equal to the original design pressure. However, suitability of this pressure shell is dependent on the details of the stiffening ribs or tees that were added to this shell when the TDT was modified. These details would have to be reviewed during final design and consideration would have to be given to the resulting stress reversals in the shell. This shell is unlikely to be found suitable for pressures of 300% or more of PUOL without some additional strengthening which would be impractical if not impossible.

d. Zone 3, from Upstream end of Northwest Corner Girder to Fan, W_{12}, and W_{13}; and Zone 1, from Fan to approximately 50 feet downstream of Fan, part of W_1.

None of this ducting is part of the original tunnel. All of it is new and was added when the TDT was rebuilt. For 150% or more of PUOL with the fan operating, the Zone 3 ducting will be subjected to lower internal pressures than the Zone 1 ducting; but both zones will have to be proof tested at the same internal pressure. It is the pressure test, therefore, that will control the design of the Zone 3 ducting. Because this new ducting, including theElliptical Corner Girders, was provided when the tunnel was rebuilt, it is safe to assume that it has never been suggested to internal operating pressures much above 3.0 psig, although it has been known to be frequently subjected to external pressures of -14.5 psig.

(1) Elliptical Corner Girders: The ability of these girders to withstand 150% or 200% of PUOL, the resulting stress reversals, and the associated pressure test is dependent on their details. The design and details of these girders will have to be carefully reviewed during final design to determine what kind of reinforcement, if any, would be required to make them suitable for the increased internal pressures. It may even be necessary to replace these girders to attain 150% or 200% of PUOL, although this is unlikely. However, it is very unlikely that these girders will be found to be suitable for pressures of 300% or more of PUOL without some additional strengthening which would be impractical if not impossible.

(2) Pressure Shell: This shell without additional reinforcement will almost certainly be suitable for 150% of PUOL and will probably be suitable for 200% of PUOL. Its suitability will depend on the welding details that were used on this shell. If full penetration butt welds were used in the longitudinal seams in the shell, in the web and flange seams in the stiffening rings, and preferably in the circumferential seams in the shell, it will be suitable for 200% of PUOL. These welding details will have to be reviewed during final design, and consideration will have to be given to the stress reversals. It is unlikely that these shells will be suitable for 300% or more of PUOL.

(3) Hinged Expansion Joint: The expansion elements and the rotation pins are certainly suitable for 150% and 200% of PUOL. The struts or ties are certainly suitable for 150% and 200% of PUOL between the pins. The tension area of these struts in the pin area as well as behind the pin will have to be reviewed during final design and consideration will have to be given to the stress reversals in all of the components. It is almost certain to be found suitable for 150% of PUOL but may require some reinforcement for 200% of PUOL. It is unlikely that any of the elements of this hinged joint would be suitable for 300% or more of PUOL.

e. Fan Drive Nacelle and Personnel Access to Nacelle

The fan drive, its nacelle, and the personnel access to the nacelle are not part of the original tunnel but were added when the tunnel was rebuilt. The leading and trailing parts of the nacelle are vented to the tunnel atmosphere and consequently are not subjected to any appreciable pressure differential. The central chamber of the nacelle and the faired personnel access through the bottom of the tunnel shell to the nacelle are both at atmospheric pressure at all times with the present operating procedures, and presumably this method of operating would be retained under higher operating pressures. These components under current operating procedures are subjected to pressures varying from about 14.5 psig internal to about 3 psig external. At 150% of PUOL the external pressure would increase to about 11.3 psig, and at 200% of PUOL to about 20.1 psig. It is probable that internal ribs would have

to be added to both of these components for a pressure of 150% of PUOL, and it is almost certain that internal ribs would have to be added for 200% of PUOL. At this pressure, stress reversals in the shell and ribs would be about 100%. Since adding external ribs is not possible because of the tunnel air flow and adding internal ribs may be extremely difficult, consideration could be given to providing a pressure-tight opening to atmosphere and pressurizing these components. Such a scheme would require either remote monitoring of the drive or having personnel working in a pressurized atmosphere under some test conditions. Each of these proposals has its own set of problems that would tend to hamper test programs. For pressures of 300% or more of PUOL it is unlikely that these shells could be reinforced sufficiently to be suitable unless they were pressurized as discussed above, and it is probable that new shells would be required.

f. Stress Reversals in Pressure Shell and Structural Components

For pressures up to 150% of PUOL stress reversals are not likely to be a problem. For 200% of PUOL the stress reversals in some areas would be approximately 100%, and the stress levels would have to be carefully reviewed during final design to determine whether or not the stress reversals could be tolerated. The stress levels and reversals for 300% or more of PUOL would almost certainly prove to be intolerable.

g. Miscellaneous Items

(1) Access Port Covers

The tension in the bolts for access covers and

the covers themselves are almost certainly suitable for pressures up to 200% of PUOL. The tension in the bolts is probably suitable for pressures up to 400% PUOL although the covers themselves may have to be replaced with stronger ones.

(2) Lighting Porthole Covers

The details of these covers are probably suitable for pressures up to 200% of PUOL, but may have to be replaced for 300% or more of PUOL.

(3) Bypass Lines and Quick Opening Valves between Zone 1 and Zone 2

The bypass ducting is part of the original tunnel and is subjected to the same pressure differentials as the Zone 1 ducting. It is almost certain to be suitable for 150% and 200% of PUOL. It is probably not suitable for 300% or more of PUOL. The four quick opening valves under present operating conditions are subjected to varying pressures up to 14.5 psig acting east and approximately 8.9 psig acting west. For 200% of PUOL the maximum westward pressure would increase to about 15.1 psig. The resulting 100% stress reversals would probably be tolerable. These valves would probably be suitable for 150% and 200% of PUOL, but would probably not be suitable for 300% or more of PUOL.

h. Proof Pressure Test

In view of the past history of this tunnel, the fact that it was originally built in 1937 for internal gage pressures, and was extensively modified for use as a vacuum tunnel (its present use) between 1955 and 1960, it should be subjected to an internal

pressure proof test of 150% of its maximum anticipated future operating pressure before any increased operating pressure is permitted whether or not any additional reinforcement is added. This proof test would have to be pneumatic since a water test is not possible.

(1) Proof Test Procedure:

(a) Button up tunnel and open both test section isolation valves. Pump tunnel down to 0.2 psia (14.5 psig external). This will test the shell of the full circuit for the maximum external operating pressure.

(b) Then close the four 36-in. bypass valves and both test section isolation valves, and vent the test section to atmosphere. This will test these six valves, the nozzle inlet fairing (W_5), and the diffuser inlet (W_{10}) for the maximum external pressure differential on these components.

(c) With all six valves remaining closed and test section remaining vented to atmosphere, vent remainder of tunnel circuit to atmosphere; and then, using air, pump tunnel circuit (but not test section) up to an internal pressure of p (see table below for magnitude of p). This will test the six valves, the nozzle inlet fairing (W_5), and the diffuser inlet (W_{10}) for 150% of the maximum internal operating pressure differential on these components.

(d) Finally, vent the tunnel circuit to atmosphere and open both test section isolation valves. Then, using air, pump the entire tunnel circuit including the test section plenum up to an internal pressure of p_2 (see table below for magnitude of p_2). This will test the pressure shell of the entire tunnel circuit to 150% of the maximum operating pressure in the stagnation chamber upstream of the nozzle inlet.

(2) Table of Test Pressures for Increments of PUOL:

% of PUOL	Internal Test Pressure, psig	
	p1	p2
125%	5.3	10.7
150%	10.4	17.0
200%	22.7	30.2
300%	43.2	56.3
400%	65.0	82.4

4. Summary of Effect on Tunnel Circuit for Several Increments of Total Operating Pressure Increases:

a. Operating Pressure Increased to 125% of PUOL.

(1) These components will not require any additional reinforcement for this pressure; Test Section airstream shell, Butterfly Valve, Diffuser Inlet, Hinged Expansion Joint, Access Port Covers, Lighting Port Covers, and four Bypass Ducts and Quick-Opening Valves.

(2) These components will probably be satisfactory without any additional reinforcement; pressure shell in Zone 1, the S.E., S.W., N.E. and N.W. corner Girders, Test Section Plenum shell, Nozzle Inlet fairing, Gate Valve, Test Section Observation Windows, Personnel Access Tunnel to Test Section, and pressure shell in Zone 3.

(3) These components may require some additional reinforcement; Control Room shell, reinforcement of opening in Control Room shell for personnel access, door attachment details for Personnel Access to Test Section, Fan Drive Nacelle, and Personnel Access Passage to Nacelle.

(4) The Observation Dome and Access Tube should be removed.

(5) The stress reversals that will occur in the pressure shell and structural components will almost certainly be acceptable because of the relatively low stress levels for most of the reversals.

b. Operating Pressure Increased to 150% of PUOL.

(1) These components will not require any additional reinforcement for this pressure; Test section airstream shell, butterfly valve, diffuser inlet, hinged expansion joint, access port covers, lighting port covers, and four bypass ducts and quick-opening valves.

(2) These components will probably be satisfactory without any additional reinforcement; pressure shell in Zone 1, southwest corner girder, test section plenum shell, nozzle inlet fairing, gate valve, test section observation windows, personnel access tunnel to test section, and pressure shell in Zone 3.

(3) These components may require additional reinforcement or replacement; the southeast, northwest, and northeast corner girders.

(4) These components will probably require some additional reinforcement; control room shell, reinforcement of opening in Control Room shell for personnel access, door attachment details for personnel access to test section, fan drive nacelle, and personnel access passage to nacelle.

(5) The Observation Dome and Access Tube should be removed.

(6) The stress reversals that will occur in the pressure shell and structural components will probably be acceptable because of the relatively low stress levels for most of the reversals.

c. Operating Pressure Increased to 200% of PUOL.

(1) These components will not require any additional reinforcement for this pressure; Test Section airstream shell, Access Port Covers and Lighting Port Covers.

(2) These components will probably be satisfactory without any additional reinforcement; pressure shell in Zone 1, Southwest Corner Girder, Test Section Plenum shell, Butterfly Valve, Diffuser Inlet, pressure shell in Zone 3, and four By-pass Ducts and Quick-Opening Valves.

(3) These components may be suitable without any additional reinforcement; Gate Valve and Test Section Observation Windows.

(4) These components may require additional reinforcement; Personnel access Tunnel to Test Section, and S.E., N.W. and N.E. Corner Girders (these Corner Girders may have to be replaced if reinforcement is required but proves to be impractical).

(5) These components will probably require some additional reinforcement; Nozzle Inlet fairing, door attachment details for personnel access to Test Section, and the net area through and behind the pins of the Hinged Expansion Joint.

(6) These components will require additional reinforcement; Control Room shell, reinforcement of opening in Control Room shell for personnel access, Fan Drive Nacelle, and Personnel Access Passage to Nacelle.

(7) The Observation Dome and Access Tube should be removed.

(8) The stress reversals that will occur in the pressure shell and structural components are significant and will require a careful review during final design to determine if the stress levels and reversals can be tolerated.

d. Operating Pressure Increased to 300% of PUOL.

(1) The Test Section airstream shell would not require additional reinforcement. The access Port covers only and Lighting Port covers only would probably not require strengthening.

(2) It is very unlikely that many, if any, of the following items would be suitable for this pressure without extensive

reinforcement which would be impractical, if not impossible, in many cases; pressure shell in Zone 1, all four Corner Girders, Test Section Plenum shell, Nozzle Inlet Fairing, Gate Valve, Butterfly Valve, Diffuser Inlet, Observation Dome and Access Tube, Control Room shell, Test Section Observation Windows, Personnel Access Door and Tunnel to Test Section, pressure shell in Zone 3, Hinged Expansion Joint, Fan Drive Nacelle, Personnel Access Passage to Nacelle, and four By-pass Ducts and Quick-Opening Valves.

5. Conclusions:

a. No further consideration will be given to increasing the structural capability of the tunnel to 300% or more of PUOL because the consideration given to this possibility to date indicates that it is impractical from a structural standpoint. Also, an examination of Figure 5, COMPARISON OF POSSIBLE MODIFICATIONS TO TDT, indicates that even if the main power of the tunnel could be increased from 20,000 HP to 50,000 HP (or through some combination of main power increase, circuit loss decrease, and auxiliary compressor system addition the same thing could be accomplished), the only thing that it would buy over a structural capability of 200% of PUOL would be an increase in tunnel performance below 0.68 Mach. No., which is below the range considered in the request for proposal for this study. The tunnel performance improvement for main power increases to 40,000 HP or 30,000 HP would be in an even lower range.

b. The stress reversals and the magnitude of the stress levels will be within acceptable limits for 125% of PUOL and will probably be within acceptable limits for 150% of PUOL;

but they may not be within acceptable limits for 200% of PUOL. This will have to be determined during final design.

c. For 150% of PUOL the reinforcement that would be required on the components itemized in paragraphs E. a. 4. and 5. could be accomplished in about four months of tunnel shut-down time. If the S.E. N.W. and N.E. Corner Girders also have to be reinforced (but not replaced), the shut-down time would increase to six months. It is assumed that all components would be worked on simultaneously, and that tunnel shut-down would not commence until after all materials were on hand and all preliminary work had been completed. Also, this shut-down time is only for the components discussed in this paragraph. The cost of this work should not be prohibitive.

d. If the stress reversals and levels for 200% of PUOL are within acceptable limits, the reinforcement that would be required on the components itemized in paragraphs E.b.5., 6., and 7. could be accomplished in about four months of tunnel shut-down time. If the S.E., N.W., and N.E. Corner Girders also have to be reinforced (but not replaced) the shut-down time could be limited to six months. The costs for this work should not be prohibitive. If these three Corner Girders would have to be replaced for 200% of PUOL, but would only have to be reinforced for 150% of PUOL (or perhaps were even okay as is), the resulting increase in tunnel

performance would not be worth the added cost and tunnel shut-down time because the resulting increase in tunnel performance is all toward the low range. Even if the main power (or through some combination, etc.) could be increased to 40,000 HP, the improvement in tunnel performance of a tunnel shell with 200% of PUOL over one with 150% of PUOL is only below 0.76 Mach. No., which is below the range discussed in the request for proposal.

APPENDIX H

MODIFICATION COSTS

SVERDRUP & PARCEL

JOB 3857 Nasa - Langley - TDT

SHEET NO. a-1 OF 7

DATE 5-22-73

COMPUTATIONS FOR Cost Estim. (Installed Costs)

BY RHW CHKD

Cost Estimate 1 - Scheme "A"; Rewind Main Drive Motor for 30,000 H.P. Rating, two-speed

	Mobilization, Field office, Final Cleanup & Demobilization	$30,000
RHW HES	Rewind Main Drive Motor to 30,000 H.P. (Inside Nacelle) (Includes additional Brushes)	$500,000
HES	Additional Circuit Cooling	$1,000,000
CCB	Power Supply Increase	$120,000
RWP	Internal Electrical & Control (New Cable, new two-speed motor control & new feeder braker)	$150,000
ALC RWP	New Liquid Rheostat ($170,000 + $50,000 for extra Sophistication Req'd. to retain present Eddy Cur. Brk.)	$220,000
	New Eddy Current Brake (Includes removal of old & install of new)	Not required with new sophisticated Liquid rheostat.
RHW	Tunnel Shell Strengthening	None Req'd.
	Increased Freon storage Capacity	None Req'd.
RHW	Fan Modifications ° *	
	New Fan Blades	$220,000
	New Fan Blade Sockets	$220,000
	* New Kingsbury Thrust/Radial Bearing	Not Req'd.
	* New Fan shaft to Motor Shaft Coupling	Not Req'd.
	Subtotal	$2,460,000
	~14% Contingency	340,000
	Total Engineering	$2,800,000

* Do not replace ° Fan Radial Brg.; Fan shaft & hub; Motor shaft, bearings, slip rings, & coupling to Eddy Current Brake; Turning Gear; Eddy Current Brake; Kingsbury Thrust/Radial Brg.; Fan to Motor Coupling.

SVERDRUP & PARCEL

JOB 3857 Nasa - Langley - TDT — SHEET NO. a-2 OF 7

COMPUTATIONS FOR Cost Estim. — DATE 5-22-73

BY RHW CHKD

KINGSBURY THRUST / RADIAL BEARING

There is no way to modify the Kingsbury Thrust bearing unless the collar on the Fan Shaft is changed which would require a new fan shaft. This would be a major modification requiring removal of the fan hub and fan shaft from the tunnel which would require removal of the N.E. elbow of the main pressure shell or cutting a very large hole into the north side of the NE elbow.

The existing Kings. thrust brg. may be suitable for the power increase to 30,000 H.P. however.

Refer Marks Handbook, Seventh Edition, pg. 8-171

The diameter (mean) of this brg. is $\frac{45.5" + 23.5"}{2} = 34.5"$

RPM	100	150	200	300	500
34.5" Brg. Capacity	160 K	177 K	189 K	210 K	220 K

These values are based on a viscosity of 150 sec. Saybolt at operating temperature. Capacity may be increased 10% to 25% if the viscosity is increased in the same proportions.

Say Thrust ≈ 505 # / blade
× 47 blades
25,000 # total

Refer Figure 1 - Operation with Freon 12 - Langley Working Paper

Say motor speed at Mach 0.8 ≈ $\frac{0.8 \text{ Mach}}{1.17 \text{ Mach}} \times 235 \text{ RPM} \approx 160 \text{ RPM}$ at max power

Say approx Mach No. at 100 RPM and max power ≈
Mach ≈ $\frac{100 \text{ RPM}}{235 \text{ RPM}} \times 1.17 \approx 0.5$ Mach

Conclusion:

The Kingsbury Thrust Bearing appears to be conservatively sized for the present drive motor and may well be suitable for a rewound drive motor to 30,000 H.P. capacity. The present oil used in the lubrication system should be analyzed by a lubrication specialist to see if a more suitable oil is available which would improve the thrust carrying capacity of the K. bearing, but it appears to be OK as it is.

If the 30,000 H.P. drive is run at 25% overload the thrust on the bearing should be approx.:

$$\text{Thrust} \approx 25^{K} \times \frac{30{,}000 \text{ H.P.}}{20{,}000 \text{ H.P.}} \times 125\% = 47^{K}, \text{ which}$$

is well below the 160^{K} allowable thrust at 100 RPM

The present lubrication system may have to be modified for increased volume flow, especially at low speeds.

Eddy Current Brake:

If we increase the main power to 30,000 H.P. and install a new liquid rheostat, why is it necessary to also install a new Eddy Current Brake? Why cannot the new liquid rheostat be designed for coarse incremental changes that differ somewhat from those of the present liquid rheostat, and that would be sized on the ability of the present Eddy Current Brake to control the new motor speed within the allowable tolerance in that new coarse incremental change?

After a discussion with Al Coffman and Bob Press (and a later conversation with W. Wunderlich) it was decided that this scheme is definitely feasible. It will require a more sophisticated liquid rheostat, but it was felt that an additional $50,000 for the rheostat (say $170,000 ~~$50,000~~) would be adequate for the added complexity. But now we are able to reuse the present eddy current brake.

SVERDRUP & PARCEL

JOB 3857 Nasa - Langley - TDT

SHEET NO. a-5 OF 7

DATE 5-21-73

COMPUTATIONS FOR Cost Estim.

BY RHW CHKD

Fan Blade Socket Wt. Take-off

1.75" x 10.5" x 14"	=	257.25	x2	=	514.5
18" x 49" x .75"	=	661.5	x1	=	661.5
18.5" x 55" x .75"	=	763.125	x1	=	763.125
3.5" x 10.5" x 14"	=	514.5	x1	=	514.5
1.75" x 43" x 12"	=	903.	x1	=	903.
.375" x 9" x 12"	=	40.5	x2	=	81.
34.5" x 22" x .25"	=	189.75	x1	=	189.75
9" x 10" x .375"	=	33.75	x2	=	67.5
10.5" x 15" x .375"	=	59.06	x2	=	118.125
17" x 1'2" x .375"	=	9.56	x2	=	19.125
2.5" x 19" x .375"	=	17.81	x2	=	36.625
16" x 21" x .1875"	=	63.	x1	=	63.

3931.875

x .263 #/in^3

1034. #

Miscellaneous Gussets ≈ 166 #

1,200 #

Say at $2.00 per pound, 47 new fan blade sockets would run

47 x 1,200 # x $3.00 = $169,200 or say $170,000

Pins 47 x 3 x $2.00 = 30,000

Total $200,000

Indications are that there is a good possibility that these Fan Blade Sockets will be satisfactory for the power increase to 30 000 H.P. See next sheet for connection between Socket and hub which appears to be satisfactory. Unless the connection between the Fan Blade and the Fan Blade Socket needs to be revised these sockets may be reusable. This would have to be reviewed during a preliminary or final design phase.

Check Shear on 3.25" ϕ pin connecting fan blade Socket to hub.

$$\text{Thrust} = \frac{60.7 + 108.5 + 166.1}{3} = \frac{335.3\ \#/ft}{3} \approx 112\ \#/ft$$

$$\sim 4.5' \times 112\ \#/' = 505\ \#/\text{blade}$$

Drag or Tangential Force = $\sim 125\ \#/' \times \sim 4.5' = 563\ \#/\text{blade}$

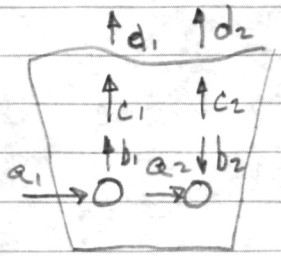
Centrifugal Force = $N = \frac{W}{g} r\omega^2$

Say Fan Blade Socket = 1200 # @ $r_1 \approx \frac{132"}{12} = 11.0'$

" Fan Blade = 130 # @ $r_2 \approx 16'$

Say ω = 235 RPM = 3.92 RPS (Frcon)

$$N = \left(\frac{1200\ \#}{32.2\ '/sec^2} \times 11' + \frac{130\ \#}{32.2} \times 16'\right) \times 3.92^2 = 7,292\ \#$$



$$a_1 = a_2 = \frac{563\ \#}{6} = 94\ \#$$

$$b_1 = b_2 \approx \frac{563\ \# \times (15.3' - 8.3') \times 12"/' }{6.75"} \times 1/3 \approx \pm 2,335\ \#$$

(7.0')

$$c_1 = c_2 \approx \frac{505\ \# \times 7.0' \times 12"/'}{24.25"} \times 1/2 \approx + 875\ \#$$

$$d_1 = d_2 \approx \frac{N}{6} \approx \frac{7292\ \#}{6} \approx + 1,215\ \#$$

$$\text{Max brg on pin} \approx \sqrt{a_1^2 + (b_1 + c_1 + d_1)^2} \approx 4,426\ \#$$

For power increase to 30,000 Hp.

$$\text{Max brg on pin} \approx \sqrt{(1.5a_1)^2 + (1.5b_1 + 1.5c_1 + d_1)^2} \approx 6,032\ \#$$

$6,032 / 4,426 \approx 1.3629$

Say Present Forces with Air in Tunnel and Fan Speed = 470 RPM

$N = 7,292\ \# \times \left(\frac{2}{1}\right)^2 = 29,168\ \#$

$d_2 = 1/6 \times 29,168\ \# = 4,862\ \#$

Max. brg. on pin $\approx \sqrt{a_1^2 + (b_1 + c_1 + d_2)^2} \approx 8,072\ \#$

There for present forces during max. fan speed in air probably exceed the forces in freon at max. speed with power increase to 30 000 H.P.

The same probably holds true for the fan blades themselves which may prove to be adequate for the increased power.

New Fan Blades°

Say Tooling	= $100,000
50 blades @ $2,000 (Includes 3 spares)	= 100,000
Total	= $200,000

Fan Blades	$200,000
Connec. Pins & Fan Blade Sockets	$200,000
Installation 10%	$ 40,000
	$440,000

SVERDRUP & PARCEL

JOB 3857 NASA - Langley - TDT

COMPUTATIONS FOR Cost Estim.

SHEET NO. b-1 OF 5

DATE May 24, 1973

BY RHW CHKD

New 50,000 hp Main Drive Motor

A	New Motor and Drive - 50,000 hp 13,600 V (includes Motor, Bearings, liquid rheostat, and Eddy Current Brake)	$3,000,000
B	Motor & Drive Installation - (includes ways, handling Brackets & cradles, miscell. equip. labor)	1,000,000
C	New Fan - (includes hub, fan blade sockets, fan blades, shaft, radial bearing, thrust/radial bearing, coupling and fan installation)	1,200,000
D	Remove old Drive & Fan from Tunnel	500,000
	Power Supply Increase	480,000
	Internal Electrical & Control (includes new cable, two-speed motor control & feeder cable)	175,000
	Additional Freon Storage	25,000
E	Additional cooling for eddy current brake, liquid rheostat and main drive motor	50,000
F	Additional Circuit Cooling	3,000,000
G	Tunnel Shell strengthening for pressure operation equal to 125% of Present Shell struct. Limit (includes Tunnel Circuit Proof Pressure Test by NASA)	200,000
H	Cut, remove, reinstall & reweld Nacelle Nose Cone, Nose of Nacelle Pressure Shell & 23'x23' hole in North side of NE Corner Elbow.	200,000
I	Unload and transport New Motor & Fan and transport and load Old Motor & Fan	60,000

New 50,000 hp Main Drive Motor (contin.)

Mobilization, Site Preparation, Field office, Cleanup and Demobilization		$50,000
Transportation Costs of Motor & Fan		50,000
	Subtotal	$9,990,000
~15%	Contingency	$1,510,000
	Total	$11,500,000

Engineering

Cost Estimate Back-up Sheet

A) New 50 000 HP Two-speed wound rotor motor 13,600 V- (includes motor, liquid rheostat*, and eddy current brake*) Assume turning gear and coupling will be reused and that new motor will be designed to fit on existing sole plate and motor cradle support.

* Use same price for Eddy Current Brake plus Liquid Rheostat or for Silicone Control Rectifier System to control speed (refer Al Coffmans 5-21-73 sketches).

Use $60.00 per h.p. for Motor plus liquid rheostat and eddy current brake. Not installed - FOB Mfg's. plant

50 000 hp x $60.00 = $3,000,000

B) Motor & Drive Installation - includes ways inside / outside tunnel leg, handling brackets & cradles, miscellaneous equipment eg. jacks, hoists, blocking, etc., & labor.
Use 1/3 x Equipment Costs = $1,000,000

C) New Fan - includes new blades, blade sockets, hub*, shaft*, radial brg.*, thrust/radial brg., and coupling & Install.

Fan blades - Tooling @ $100,000 & 50 new blades at $2000.00 / blade = $100,000 - Total =	$200,000
47 Fan blade Sockets & Conne. Pins	200,000
Hub - say 80 tons @ $1.00 per pound	160,000
Shaft - say 40 tons @ $1.00 per pound	80,000
Rad. Brg. @ $20,000; Coupling @ $10,000; Thrust/Radial Brg. @ $50 000 =	80,000
30 Fixed stator Blades, $18,000; 40 Adjustable stator Blades, $72 000 =	90,000
24 Adjustable Prerotation Stator Vanes	50,000
Installation @ 40%	340,000
Total =	$1,200,000

* The hub, shaft and radial bearing might be able to be

reused. A detailed analysis of these items may indicate their suitability, but it would probably depend on designing a new roller thrust bearing (split) to fit the shoulder on the existing shaft.

D) Remove old Drive & Fan from Tunnel
(Install. of new Fan & Drive is estimated as $280,000 to $1,000,000) Say removal costs = $500,000

E) Additional cooling for Eddy Current Brake, liquid rheostat, & main drive motor Say $50,000

F) Additional Circuit Cooling
(50,000 hp - 20,000 hp) x $100/hp = $3,000,000

G) Tunnel Shell strenthening for operating pressure equal to 125% of Present shell Struct. Limit. Additional reinf. should be limited to isolated details - no major items - Say $200,000

H) Cut, remove, reinstall & reweld Nacelle Cone, Nose of Nacelle Pressure Shell, & 23'x23' hole in north side of N.E. Elbow.
Say 1 supt., 8 welders & 2 foremen, 8 iron workers & 1 foreman = 20 @ $200/day aver. = $4000 per day
Say 2 weeks to cut & remove
" 6 " to reinstall & reweld
8 weeks x 5 days/wk x $4,000/day = $160,000
Crane & operator for 8 WKS + miscell. equip. = 40,000
Total = $200,000

I Unload and transport New Motor & Fan and Transport and load Old Motor & Fan.

Two crawler cranes of capacity in excess of 120 Tons for one month.

$7,000 / mo. each crane
3,600 / mo. each operator
2,400 O.H. & Profit (25%)
$13,000 per mo. each crane
x2 cranes
$26,000
4000 Lowboys or dollies & miscell.
$30,000 equip costs
20,000 Excavation of barge slip & Construc. & removal of unloading slip.
10,000 Road Repair & cleanup
$60,000 Total

SVERDRUP & PARCEL

JOB 3857 Nasa - Langley - TDT SHEET NO. C-1 OF 1
DATE May, 1973
COMPUTATIONS FOR Cost Estim. BY RHW CHKD

10,000 hp Two-Compressor Auxiliary System - Freon Only

1. Soil Borings		$ 3,000
2. Contractor's Mobilization, Field office, Final Cleanup & Demobilization		40,000
3. Sitework		10,000
4. 2 Coolers, including Installation		250,000
5. One Cooling Tower, including Fdn. ($10,000) & Install.		160,000
6. Ducting :		
a) Shell & Reinforcement	$ 535,000	
b) Expansion Joints	130,000	
c) Valves	77,000	
d) Turning Vanes	50,000	
e) Bolting Flanges	14,000	
f) Ducting Supports, Anchors, Guides & Foundations	135,000	
g) Reinf. & Midific. of Test Sect. for Inlet & Outlet	95,000	
Total Duct.		1,036,000
7. Concrete Trench for 10' ϕ Duct.		84,000
8. Two Single Stage Compressors & Motors with Gearbox, includes Install., Checkout, O.H. & Profit		2,980,000
9. Compressor Foundations 2 @ $ 18,000		36,000
10. Compressor Building		400,000
11. Power Supply Increase		90,000
12. Electrical Work & Equipment		140,000
Subtotal		5,229,000
Contingency & Omissions @ 15%		791,000
Total		$ 6,000,000

Architect-Engineer Fee —

SVERDRUP & PARCEL

JOB 3857 NASA - Langley - TDT SHEET NO. d-1 OF 1

DATE May, 1973

COMPUTATIONS FOR Cost Estimate BY RHW CHKD

10,000 hp. Four-Compressor Auxiliary System - Freon or Air

1. Soil Borings		$3,000
2. Contractor's Mobilization, Field office, Final Cleanup & Demobilization		40,000
3. Site work		10,000
4. Four Coolers, including Install.		500,000
5. One Cooling Tower, including Fdn ($10,000) & Install		160,000
6. Ducting:		
a) Shell & Reinforcement	$577,000	
b) Expansion Joints	232,000	
c) Valves	166,000	
d) Turning Vanes	58,000	
e) Bolting Flanges	22,000	
f) Ducting Supports, Anchors, Guides & Foundations	143,000	
g) Reinf. & Modific. of Test sect. for Inlet & Outlet	95,000	
Total Ducting		1,293,000
7. Concrete Trench for 10'ϕ Duct		84,000
8. Four Single Stage Compressors & Motors with Gearbox, includes Install, Checkout, O.H., & Profit		5,410,000
9. Compressor Foundations 2 @ $29,000		58,000
10. Compressor Building		600,000
11. Power Supply Increase		90,000
12. Electrical Work & Equipment		140,000
Sub total		8,388,000
Contingency & Omissions @ 15%		1,212,000
Total		$9,600,000

Architect-Engineer's Fee —

15,000 hp Two-Compressor Auxiliary System with 30,000 hp Rewound Main Drive Motor - Freon Only

1. Soil Borings		$3,000
2. Contractor's Mobilization, Field office, Final Cleanup & Demobilization		40,000
3. Site work		10,000
4. Two Coolers, Including Install.		250,000
5. One Cooling Tower, including Fdn. ($12,000) & Instal.		222,000
6. Ducting:		
a) Shell & Reinforcement	$535,000	
b) Expansion Joints	130,000	
c) Valves	77,000	
d) Turning Vanes	50,000	
e) Bolting Flanges	14,000	
f) Ducting Supports, Anchors, Guides & Foundations	135,000	
g) Reinf. & Modific. of Test Sect. for Inlet & Outlet	95,000	
Total Ducting		1,036,000
7. Concrete Trench for 10' ϕ Duct		84,000
8. Two Single Stage Compressors & Motors with Gearbox, includes Install., Checkout, O.H. & Profit		3,160,000
9. Compressor Foundations 2 @ $18,000		36,000
10. Compressor Building		400,000
11. Power Supply Increase		220,000
12. Electrical Work & Equipment		165,000
13. Rewind Main Drive Motor to 30,000 hp rating, two-speed (Inside Nacelle - includes additional brushes)		500,000
14. Additional Circuit Cooling		1,000,000
Sheet Subtotal		$7,126,000

(Continued on next page)

Previous sheet subtotal	$7,126,000
15. Internal Electrical & Control (New Cable, new two-speed motor control & new feeder braker)	150,000 — —
16 New Liquid Rheostat ($170,000 + $50,000 for extra sophistication req'd. to retain Eddy Current Brake	220,000 —
17. Tunnel Shell Strengthening	None Req'd.
18. Increased Freon Storage Capacity	None Req'd.
19. Fan Modifications % *	
a) New Fan Blades	220,000
b) New Fan Blade Sockets	220,000
Subtotal	7,936,000
Contingency & Omissions @ 15%	1,164,000
Total	$9,100,000
Architect-Engineer's Fee	—

* Do not replace % fan radial brg; Kingsbury thrust / radial brg.; fan shaft & hub; fan-to-motor coupling; motor shaft, bearings, slip rings, and coupling-to-Eddy Current Brake; Turning Gear; and Eddy Current Brake.

SVERDRUP & PARCEL

JOB 3857 NASA - Langley - TDT SHEET NO. f-1 OF 2
DATE May, 1973
COMPUTATIONS FOR Cost Estimate BY RHW CHKD

15,000 hp Four-Compressor Auxiliary System with 30,000 hp Rewound Main Drive Motor - Freon & Air

1. Soil Borings		$3,000
2. Contractor's Mobilization, Field office, Final Cleanup & Demobilization		40,000
3. Site work		10,000
4. Four Coolers, Including Install.		500,000
5. One Cooling Tower, including Fdn. ($12,000) & Inst.		222,000
6. Ducting to		
a) Shell & Reinforcement	$577,000	
b) Expansion Joints	232,000	
c) Valves	166,000	
d) Turning Vanes	58,000	
e) Bolting Flanges	22,000	
f) Ducting Supports, Anchors, Guides & Foundations	143,000	
g) Reinf. & Modific. of Test Sect. for Inlet & Outlet.	95,000	
Total Ducting		1,293,000
7. Concrete Trench for 10'ϕ Duct		84,000
8. Four Single Stage Compressors & Motors with Gearbox, includes Install., Checkout, O.H. & Prof.		5,600,000
9. Compressor Foundations 2 @ $29,000		58,000
10. Compressor Building		600,000
11. Power Supply Increase		220,000
12. Electrical Work & Equipment		165,000
13. Rewind Main Drive Motor to 30,000 hp rating, two-speed (Inside Nacelle - includes additional brushes)		500,000
14. Additional Circuit Cooling		1,000,000
Sheet Subtotal		$10,295,000

(continued on next page)

15,000 hp Four-Compressor Auxiliary System with 30,000 hp Rewound Main Drive Motor - Freon & Air

Previous sheet Subtotal	$10,295,000
15. Internal Electrical & Control (New Cable, new two-speed motor control & new feeder braker)	150,000
16. New Liquid Rheostat ($170,000 + $50,000 for extra sophistication req'd. to retain Eddy Current Brake	220,000
17. Tunnel Shell Strengthening	None Req'd
18. Increased Freon Storage Capacity	None Req'd.
19. Fan Modifications ° *	
a) New Fan Blades	220,000
b) New Fan Blade Sockets	220,000
Subtotal	$11,105,000
Contingency & Omissions @ 15%	1,695,000
Total	$12,800,000

Architect-Engineer's Fee —

* Do not replace ° fan radial brg.; Kingsbury thrust/radial brg.; fan shaft & hub; fan-to-motor coupling; motor shaft, bearings, slip rings, and coupling-to-Eddy Current Brake; Turning Gear; and Eddy Current Brake.